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# **LEAD AND COPPER RULE**

## **GUIDANCE MANUAL**

### **VOLUME II: Corrosion Control Treatment**



Printed on Recycled Paper

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# **LEAD AND COPPER RULE GUIDANCE MANUAL**

## **Volume II: Corrosion Control Treatment**

**for**

**Drinking Water Technology Branch  
Drinking Water Standards Division  
Office of Ground Water and Drinking Water  
U.S. Environmental Protection Agency  
Washington, D.C.**

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by**

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**September 1992**

# Preface

On June 7, 1991, the U.S. Environmental Protection Agency promulgated NPDWRs for lead and copper. EPA is developing a guidance manual in two volumes to assist water systems and State regulatory agencies in implementing the technical requirements of the rule. The first volume of the *Lead and Copper Rule Guidance Manual* addressed the monitoring requirements of the rule. The second volume of the *Lead and Copper Rule Guidance Manual* concentrates on corrosion control treatment and lead service line replacement.

This volume focuses on the evaluation of corrosion control treatment options and optimization of the full-scale treatment. The manual discusses the procedures that can be used by water systems to determine the appropriate corrosion control treatment. The manual discusses the available testing protocols for conducting the demonstration studies that many large systems will be required to perform prior to making their treatment

recommendation to the State. For smaller systems, the manual contains a summary of case studies separated by the raw water quality to assist these systems in making their treatment recommendation to the State. The manual also provides guidance to assist State regulatory agencies in reviewing data from corrosion control studies and in specifying optimal water quality parameters. An additional chapter provides guidance on the lead service line replacement requirements. The subject matter discussed in this chapter includes what constitutes a replacement of a lead service line, replacement schedules, and the criteria for discontinuing lead service line replacements.

I hope that this volume of the manual will be a practical tool for water systems and State regulatory agencies in implementing the corrosion control treatment and lead service line replacement requirements of the lead and copper rule.

James R. Elder

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TERM	DESCRIPTION
<b>Non-Parametric Statistics</b>	Statistical measures of relative behavior between two or more sets of data not predicated on the data being normally distributed.
<b>Passivation</b>	A corrosion control technique which incorporates the pipe materials into metal/hydroxide/carbonate compounds intended to protect the pipe.
<b>pH/Alkalinity Adjustment</b>	The addition of chemicals to modify the pH and/or alkalinity to produce a less corrosive water.
<b>Phosphate Inhibitor</b>	A phosphate based chemical intended to reduce corrosion when added to water.
<b>Pipe Insert</b>	Pipe sections used to evaluate the rate of corrosion by insertion into piping systems.
<b>Pipe Loop</b>	An experimental apparatus consisting of several feet of pipe complete with joints, elbows, and connections for flow through testing.
<b>Pipe Rig</b>	The overall apparatus used for flow through testing which may consist of several individual pipe loops.
<b>Precipitation</b>	The shifting of chemical equilibria to cause the formation of a solid protective coating, usually calcium carbonate, on interior pipe surfaces.
<b>Sample Plan</b>	A description of the sampling locations and criteria for targeted sample sites for first-draw tap, distribution system, and point of entry samples.
<b>Sample Pool Category</b>	The sample pool category of a PWS reflects the relative priority of targeted sample sites able to be identified and included in the sample plan for first-draw tap samples.
<b>Small Water System</b>	A water system that serves 3,300 persons or fewer.
<b>Silicate Inhibitor</b>	A silicate based chemical intended to reduce corrosion when added to water.
<b>Source Water Sample</b>	Samples collected at the entry point(s) to the distribution system representative of each source of supply after treatment.
<b>Source Water Treatment</b>	Removal of lead and/or copper from the source of supply.
<b>Static Testing</b>	An experimental approach that retains the testing surfaces within standing water.
<b>Weight-Loss Measurement</b>	An approved method of determining the amount of metal lost to corrosion from a pipe insert or coupon.

**ACRONYM****DEFINITION**

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<b>AC</b>	Asbestos-Cement.
<b>AL</b>	Action Level - the level of lead or copper in first-draw tap samples which when exceeded triggers additional compliance actions on the part of PWSs.
<b>ASTM</b>	The American Society for Testing and Materials.
<b>AWWA</b>	The American Water Works Association.
<b>AWWARF</b>	The American Water Works Association Research Foundation.
<b>BAT</b>	Best Available Technology.
<b>CCPP</b>	Calcium Carbonate Precipitation Potential.
<b>CT</b>	The product of disinfectant concentration (C) in mg/L and the effective contact time (T) in minutes.
<b>CT<sub>act</sub></b>	Actual CT value achieved across a single disinfection segment.
<b>CT<sub>req</sub></b>	Required CT value for a specific level of <i>Giardia</i> or virus inactivation as a function of temperature, pH, and in the case of free chlorine, disinfectant residual.
<b>Cu</b>	Copper
<b>Cu-POE</b>	Copper concentration at Point of Entry.
<b>DBPs</b>	Disinfection By-Products
<b>DBPR</b>	Disinfection By-Products Rule
<b>CWS</b>	Community Water System
<b>GAC</b>	Granular Activated Carbon
<b>GWDR</b>	Ground Water Disinfection Rule
<b>HPC</b>	Heterotrophic plate count.
<b>LCR</b>	Lead and Copper Rule.
<b>LSL</b>	Lead Service Line.
<b>LSLRP</b>	Lead Service Line Replacement Program.
<b>NTNCWSs</b>	Non-Transient, Non-Community Water Systems.
<b>NSF</b>	National Sanitation Foundation.
<b>Pb</b>	Lead
<b>Pb/Cu-POE</b>	Lead and copper samples collected at the points of entry to the distribution system representative of each source of supply after treatment.
<b>Pb/Cu-TAP</b>	Lead and copper samples collected as first-draw tap samples from targeted sample sites.



<b>ACRONYM</b>	<b>DEFINITION</b>
<b>POE</b>	Points of Entry to the distribution system representative of each source of supply after treatment. Used to describe source water monitoring activity.
<b>PQL</b>	Practical Quantitation Level
<b>PWS</b>	Public Water System
<b>QA/QC</b>	Quality Assurance and Quality Control measures to ensure reliable data are collected.
<b>SDWA</b>	Safe Drinking Water Act of 1974 as amended in 1986.
<b>SWTR</b>	Surface Water Treatment Rule.
<b>SOCs/IOCs</b>	Synthetic Organic Chemicals/Inorganic Chemicals - Classes of chemical compounds.
<b>SDSTTHM</b>	Simulated Distribution System Total Trihalomethanes.
<b>TCR</b>	Total Coliform Rule.
<b>THAAs</b>	Total HaloAcetic Acids.
<b>THM</b>	Trihalomethane.
<b>TTHMs</b>	Total Trihalomethanes.
<b>WQP</b>	Water Quality Parameters, defined in the Rule to include pH, temperature, conductivity, alkalinity, calcium, orthophosphate, and silica.
<b>WQP-POE</b>	Water Quality Parameters measured at the Points Of Entry to the distribution system representative of each source of supply after treatment.
<b>WQP-DIS</b>	Water Quality Parameters measured at representative locations throughout the DIStribution system.
<b>WTP</b>	Water Treatment Plant.
<b>90%Cu-Tap</b>	The 90% copper level for first-draw tap samples collected at targeted sample sites.
<b>90%Pb-Tap</b>	The 90% lead level for first-draw tap samples collected at targeted sample sites.
<b>[(90%Pb-Tap) - (Pb-POE)]</b>	The difference between the 90% lead level for first-draw tap samples collected at targeted sample sites and the highest respective lead level measured at the points of entry to the distribution system.

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## *Glossary of Terms<sup>1</sup>*

<b>TERM</b>	<b>DESCRIPTION</b>
<b>Calcium Adjustment</b>	The addition of calcium to shift chemical equilibria to produce a less corrosive water.
<b>Consecutive System</b>	A public water system (PWS) which receives treated water from another PWS where the interconnection of the systems justifies treating them as a single system for monitoring purposes.
<b>Corrosion Inhibitor</b>	A chemical, usually phosphate or silicate based, that can be used to reduce corrosion.
<b>Corrosion Control Study</b>	A desk-top evaluation, static testing, or flow through testing designed to identify optimal corrosion treatment.
<b>Corrosion Control Treatment</b>	Treatment to minimize the dissolution of lead and/or copper during water delivery to consumers.
<b>Coupon</b>	Piece of metal used to evaluate the rate of corrosion by insertion into piping systems.
<b>Demonstration Testing</b>	Flow through or static testing methods used to illustrate the effectiveness of a particular corrosion control treatment.
<b>Desk-Top Evaluation</b>	An office study which compiles historical information and literature to assist in determining appropriate corrosion control treatment.
<b>Flow-Through Testing</b>	An experimental approach which uses a pipe loop(s) or other apparatus that provides moving water to contact the testing surfaces.
<b>First-Draw Tap Sample</b>	One-liter sample collected from the kitchen or bathroom cold-water faucets of targeted sample sites representing water standing in the interior piping for at least six hours.
<b>Large Water System</b>	A water system that serves more than 50,000 persons.
<b>LSL Sample</b>	One-liter samples collected from locations served by lead service lines (LSLs) representing water standing in the LSL for at least six hours.
<b>Materials Survey</b>	An investigation of the materials used in home plumbing and service lines to assist PWSs in located targeted sample sites.
<b>Medium-Size Water System</b>	A water system that serves greater than 3,300 and less than or equal to 50,000 persons.

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<sup>1</sup>This glossary provides general descriptions of some of the technical terms used in this manual. Some of these terms are also defined in the lead and copper rule (see 40 CFR section 141.2). The definitions in this document, although worded somewhat differently, are intended to be consistent with the Agency's regulatory definitions.

# Chapter 1.0 — Introduction

The Lead and Copper Rule (LCR) was promulgated by EPA on June 7, 1991 as a treatment technique requirement with major provisions to be implemented over the following decade. The public water systems (PWSs) that are subject to compliance with the LCR are community water systems and non-transient non-community water systems. These PWSs must either demonstrate that optimal treatment has been installed to control lead and copper or else that the existing lead and copper levels in consumers' tap water are below acceptable levels. In addition to the water treatment requirements contained in the LCR, public education and lead service line (LSL) replacement provisions are part of the lead and copper national primary drinking water regulations.

In order to assist States in implementing the requirements of the LCR, the EPA has issued the LCR Guidance Manual. Information regarding all components of the Rule are discussed in the Guidance Manual, along with supporting suggestions and direction for State and PWS actions which may be needed to fully implement the Rule according to its intent.

The LCR Guidance Manual has been issued in two volumes and is intended to assist States and PWSs alike in furthering their understanding of the LCR and its implementation. The first volume was released by EPA in September 1991 and focuses on the monitoring portion of the Rule. This second volume presents guidance on implementing optimal corrosion

control treatment and the LSL replacement aspects of the LCR. A separate document has been prepared to assist PWSs in developing and conducting an effective public education program in response to the LCR (USEPA, 1992).

The information presented in the LCR Guidance Manual is not limited to the strict terms of the LCR. Supplemental information that may be useful to PWSs is also provided regarding such topics as performing corrosion studies, evaluating material survey data for LSL replacement, and formulating recommendations for optimal treatment. Table 1-1 presents the location of selected "topics" in which most PWSs and/or State agencies would be interested.

It is not the intent of the LCR Guidance Manual to be an authoritative reference on corrosion control - in theory or in practice - but, rather, to (1) provide direction about the implementation of the corrosion control aspects of the LCR; (2) indicate sources of additional information regarding the application of theoretical and practical aspects of corrosion control treatment/evaluations; and (3) present a logical and reasonable direction for evaluating optimal corrosion control treatment and performance for PWSs.

The Lead and Copper Guidance Manual is intended to provide supporting direction to States and public water suppliers so that the requirements of the Lead and Copper Rule may be achieved. The focus of the manual is to supplement materials readily available in the literature, referring

## INTRODUCTION

to these information sources for further reading where appropriate, and to provide practical suggestions and recommendations for accomplishing the objectives of the Rule. This document is designed to provide technical guidance to primacy agencies administering the SDWA as they exercise their judgment in implementing the national primary drinking water regulations for lead and copper. This guidance is a general statement of policy which does not establish a binding norm on primacy

agencies or public water systems and is not finally determinative of the issues addressed. Decisions made in any particular case will be governed by the applicable provisions of the SDWA and 40 CFR Parts 141 and 142.

### ***1.1 Reference***

USEPA. 1992. *Lead in Drinking Water Regulation: Public Education Guidance*. Office of Water (Washington, D.C.).

**Table 1-1. Topical Locator by Subject Matter for Lead and Copper Rule Guidance Manual**

Subject Matter	LCR Guidance Manual — Volume II									LCR GM VOL. 1 *	LCR GM Pub. Ed. **
	Chapters						Appendices				
	1	2	3	4	5	6	A	B	C		
Requirements by System Size											
Small		✓	✓	✓	✓	✓				✓	✓
Medium		✓	✓	✓	✓	✓				✓	✓
Large		✓	✓	✓	✓	✓				✓	✓
Principles of Corrosion			✓				✓				
Corrosion Control Treatment Alternatives			✓								
Regulatory Requirements											
Intent of the LCR	✓										
Who Must Perform Studies		✓									
Corrosion Study Requirements		✓									
Recommending Treatment		✓	✓	✓							
Setting Operational Criteria					✓						
Replacing LSLs						✓					
State Actions		✓	✓	✓	✓	✓					
Monitoring Requirements					✓	✓				✓	
Public Education											✓
Desk-Top Evaluations											
Steps in Desk-Top Evaluations			✓								
Source Water Treatment Guidelines			✓								
Suggested Treatment by Water Quality Criteria			✓				✓				
Constraints in Defining Optimal Treatment			✓								
Reporting Forms & Checklists			✓								
Case Studies			✓					✓			

**Table 1-1. Topical Locator by Subject Matter for Lead and Copper Rule Guidance Manual (continued)**

Subject Matter	LCR Guidance Manual — Volume II									LCR GM VOL. 1 *	LCR GM Pub. Ed. **
	Chapters						Appendices				
	1	2	3	4	5	6	A	B	C		
Demonstration Testing				✓							
Scope of Studies				✓							
Organization				✓							
Flow-Through Testing				✓							
Static Testing				✓							
Measurement Techniques				✓							
Data Handling				✓						✓	
Non-Parametric Statistics				✓						✓	
Secondary Testing Programs				✓							
QA/QC Components				✓							
Examples				✓					✓		
Recommending Optimal Treatment		✓	✓	✓					✓		
Operating Full-Scale Treatment											
Setting Operational Criteria					✓						
Start-Up Operations					✓						
Troubleshooting					✓						
Implementing Optimal Treatment					✓						
Examples					✓				✓		

\* USEPA. 1991. *Lead and Copper Rule Guidance Manual — Volume 1*. Office of Ground Water and Drinking Water (Washington, D.C.).

\*\* USEPA. 1992. *Lead in Drinking Water — Public Education Guidance*. Office of Ground Water and Drinking Water (Washington, D.C.).



## Chapter 2.0 — Regulatory Requirements for Corrosion Control Studies

The regulatory requirements in the LCR for corrosion control studies are presented below with recommendations regarding the implementation of these requirements by primacy agents, namely state drinking water authorities.

### 2.1 *Large PWSs*

Large PWSs subject to the provisions of the LCR are any community water system (CWS) or non-transient non-community water system (NTNCWS) which serves populations over 50,000 people. All large PWSs are required to define and maintain optimal corrosion control treatment within their jurisdiction. This may be the treatment currently in-place or an alternative treatment recommended as a result of performing a corrosion control study.

#### 2.1.1 *Regulatory Requirements.*

The Rule (141.82(c), 56 FR 26550) specifies six conditions to be met when performing a corrosion control study as described below:

- Evaluate the effectiveness of each of the following treatment and, if appropriate, any combinations of these approaches:
  - Alkalinity and pH Adjustment
  - Calcium Hardness Adjustment, and
  - Phosphate- or silicate-based corrosion inhibitors.
- Collect data from pipe rig/loop tests, metal coupon tests, partial-system tests (full-scale), or from documented, analogous treatments used in or tested at other systems of similar size, water chemistry, and distribution system configuration.
- Analyze the following water quality parameters in the course of testing: lead, copper, pH, alkalinity, calcium, conductivity, water temperature, and orthophosphate or silicate when an inhibitor containing the respective compound is used.
- Identify constraints (chemical or physical) which may limit the application of a particular treatment option. The existence of one of the following conditions should be documented as part of this process:
  - A particular corrosion control treatment has adversely affected other water treatment processes when used by another PWS with comparable water quality characteristics; and/or,
  - From the experience of the PWS, a particular corrosion control treatment was found to be ineffective and/or to adversely affect other water treatment processes.
- Assess the secondary impacts due to the effect of corrosion control treatment on other water treatment processes.

## REGULATORY REQUIREMENTS FOR STUDIES

- **Recommend to the State** the optimal corrosion control treatment as identified by the PWS based on an analysis of the available data with supporting documentation and rationale.

While each of the above elements present important pieces of a corrosion control study, the organization and execution of a study are left to the PWS.

### 2.1.1.1 Scope of testing activities.

By requiring all systems conducting studies to evaluate specific treatment alternatives, EPA did not intend for each PWS to construct pipe rigs or conduct bench-scale tests to accommodate any and all treatment options. EPA anticipated that preliminary screening or "desk-top" evaluations would be utilized as an initial step to limit study comparisons and costs. Alternatives would generally be screened on the basis of available findings from: (1) other corrosion control studies for systems with comparable water quality; (2) theoretical and applied research efforts; and (3) the potential adverse impacts associated with treatment modifications. As a result of the desk-top evaluation, the most feasible alternatives can be selected (at most, two or three treatment options) for additional evaluation through demonstration testing. EPA believes that, in certain cases, the results of the desk-top evaluation could suffice in the selection of optimal treatment, and additional testing may not be required. However, any PWS that does not conduct a thorough evaluation of its treatment recommendation must realize the risks involved. A desk-top evaluation considers alternatives based on the experience of other PWSs and product manufacturers' recommendations.

As each PWS has a unique supply, treatment, and distribution system, assurance that the recommended treatment will be effective is lacking without actual demonstration testing.

As discussed previously, demonstration testing may not be necessary for some large PWSs to identify optimal treatment. Table 2-1(a) presents a recommended matrix of the minimum degree of testing to be performed by large PWSs based on the results of initial monitoring for lead. The only provision of the Rule which classifies the existing treatment of large PWSs as optimized for corrosion control is when the difference between the 90%Pb-TAP and Pb-POE is less than the lead PQL for each six-month period of the initial monitoring program. By definition, the PQL for lead is 0.005 mg/L; and the lead value for the source water used in this determination is the highest source water lead concentration. If this condition is met, then no study or testing is required. However, States may consider the presence of copper in tap samples when determining whether the existing treatment is optimized.

Large PWSs, while not experiencing problems with lead corrosion (when  $[(90\% \text{ Pb-Tap}) - (\text{Pb-POE})] < \text{PQL}$ ), may find elevated levels of copper for which corrosion control treatment would be warranted. The recommended level of effort for corrosion control studies by large PWSs based on copper is presented in Table 2-1(b).

### 2.1.1.2 Source water treatment.

PWSs are only required to monitor lead and copper at the points of entry (Pb/Cu-POE) if either AL is exceeded on

**Table 2-1a. Minimum Recommended Corrosion Control Study Components for Large PWSs. Based on Lead Levels**

90th Percentile Tap Lead Level, $\mu\text{g/L}$	Source Water (POE) Lead Level, $\mu\text{g/L}$		
	Pb-POE < PQL	PQL < Pb-POE < 10	Pb-POE > 10
90% Pb-TAP < PQL	None Required	-----	-----
PQL < 90% Pb-TAP < 10	If [(90% Pb-TAP)-(Pb-POE)]<PQL, then None Required; Otherwise, Desk-Top Evaluation	None Required	-----
10 < 90% Pb-TAP < 15	Desk-Top Evaluation	If [90% Pb-TAP)-Pb-POE)]<PQL, then None Required; Otherwise, Desk-Top Evaluation	No Corrosion Control Testing Source Water Treatment Recommended or Required
90% Pb-TAP > 15	Desk-Top Evaluation and Demonstration Testing	Desk-Top Evaluation and Demonstration Testing	If [90% Pb-TAP)-Pb-POE)]<PQL, then only Source Water Treatment Required; Otherwise, Desk-Top Evaluation and Demonstration Testing and Source Water Treatment Recommended or Required

**Table 2-1b. Recommended Corrosion Control Study Components for Large PWSs. Based on Copper Levels**

90th Percentile Tap Copper Level, $\mu\text{g/L}$	Source Water (POE) Copper Level, $\mu\text{g/L}$	
	Cu-POE > AL	Cu-POE < AL
90% Cu-Tap > 1.3 mg/L	Desk-Top Evaluation, Demonstration Testing* and Source Water Treatment Required	Desk-Top Evaluation and Demonstration Testing*
90% Cu-Tap < 1.3 mg/L	-----	None Required

\* The focus of the desk-top evaluation and demonstration testing should be to select a corrosion treatment process that will reduce copper levels without adversely affecting lead levels.

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the basis of first-draw tap samples. Systems may choose to monitor the source water contribution of these metals simultaneously with first-draw tap sampling in order to determine whether the existing treatment is optimal with regard to corrosion control (90%Pb-Tap - Pb-POE < PQL). Otherwise, this monitoring must be completed within six months of exceeding the lead or copper AL.

Source water treatment recommendations must be submitted to the State within six months of exceeding an AL for any system. Guidelines for source water treatment needs are presented in chapter 3.0 (see Table 3-5). If the source water is contributing more than the AL for either lead or copper, then source water treatment is required. In those cases where a significant amount of lead or copper is present, then treatment is recommended in order to reduce the overall lead or copper exposure and to assist PWSs in meeting the ALs in future monitoring events. Table 3-5 also shows that source water treatment is optional when moderate levels of metals are found, and unnecessary when very low levels of either lead or copper are present.

In those cases where systems find elevated levels of lead or copper at the points of entry, the sources of supply (raw water) should be monitored prior to treatment and at various stages within the existing treatment facility (if currently treating the supply) to determine the source of the metals. This monitoring will also assist in assessing the performance of the existing treatment systems to remove lead and copper.

Several types of treatment may be appropriate for removal of lead and copper.

EPA specified the following techniques within the LCR (USEPA, 1991):

- Ion Exchange
- Reverse Osmosis
- Lime Softening
- Coagulation/Filtration

If a PWS is currently providing conventional treatment (whether alum or ferric coagulation, iron/manganese removal, or lime softening), optimizing these treatment processes may improve lead and copper removals. If treatment is not available, package treatment units for any of the above technologies may be installed at individual wellheads (especially when the elevated metals are contributed by a small number of individual wells) or at a centralized treatment location. In the case of elevated copper, better control or elimination of copper sulfate applications may reduce the background level of copper for some surface water supplies.

States must respond to the recommendations for source water treatment within six months. If required, PWSs have 24 months to install source water treatment once approved by the State. For large PWSs, the installation of source water treatment could precede corrosion control treatment by as much as 18 months. Follow-up monitoring for Pb/Cu-POE and first-draw lead and copper tap samples will occur simultaneously after corrosion control treatment has been installed.

### ***2.1.2 State Actions and Decisions.***

Primacy Agencies, or States, are responsible for the review of corrosion study reports which support the PWS's recommendation regarding optimal

## REGULATORY REQUIREMENTS FOR STUDIES

corrosion control treatment. State approval for study design and implementation is not required, although it would clearly benefit most PWSs to involve States in the planning of a corrosion control study so that the decisions and criteria used in selecting optimal treatment are acceptable to all parties.

In cases where the lead or copper ALs are exceeded during initial monitoring, PWSs must submit source water monitoring results and a source water treatment recommendation to the State within six months. After an additional six-month period, States must determine whether source water treatment is required. When treatment is necessary, PWSs have 24 months to install the treatment facilities and have them operational.

### ***2.2 Small and Medium Size PWSs***

Small and medium-size PWSs are any CWS or NTNCWS serving 3,300 people or less and 3,300 - 50,000 people, respectively. Corrosion control studies are not required for these systems unless an AL is exceeded.

#### ***2.2.1 Regulatory Requirements.***

The LCR requires small and medium-size PWSs to perform initial first-draw tap monitoring for lead and copper at targeted sites located within their service area. If either the lead or copper AL is exceeded during a six-month monitoring period, the PWS must submit recommendations for optimal treatment to the State within six months of exceeding the AL. For example, a small PWS begins tap sampling for lead

and copper in July 1993 and by the end of the first monitoring event (December 1993), the system discovers that the lead AL was exceeded. The monitoring results must be reported to the State by January 11, 1994 and recommendations for optimal treatment are to be provided to the State by July 1, 1994. The detailed time frames for small and medium-size PWSs to comply with the corrosion control and source water treatment requirements of the LCR are presented in Tables 2-2 and 2-3.

The treatment recommendations to be generated include source water and corrosion control treatment components. Upon exceeding an AL during initial monitoring, a small or medium-size PWSs must also monitor lead and copper at each point of entry (POE) to the distribution system to determine whether excessive metals are being contributed by the source water. The POE lead and copper levels must also be reported to the State in conjunction with the system's recommendations for optimal treatment.

The recommendation for optimal treatment (source water and/or corrosion control) may be based on well-documented desk-top evaluations, and need not be determined by demonstration testing of alternative treatment approaches. However, states may require a system to perform such testing, in which case an additional 18 months would be provided to complete the corrosion control study. The requirement to include demonstration testing in the determination of optimal treatment for small and medium-size PWSs does not have to rely on the PWS performing the demonstration testing themselves if a study is underway by another PWS with comparable water quality characteristics.

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**Table 2-2. Timeline for Small PWSs to Comply with the Corrosion Control and Source Water Treatment Requirements\***

PWS Action	Date	Submission to State
First Six-Month Initial Monitoring Period Results** • Exceed ALs	Jan. 11, 1994	Form 141-A and Monitoring Results: Pb/Cu-TAP; WQP-DIS; WQP-POE
Desk-Top Treatment Evaluation Begins	Jan. 1, 1994	
Source Water Monitoring Results	July 1, 1994	Pb/Cu-POE
Treatment Recommendation	July 1, 1994	Treatment recommendations for corrosion control and/or source water treatment
State Requires Corrosion Studies	Jan. 1, 1995	As necessary, State notifies PWSs required to perform corrosion studies
State Approves/Designates Treatment (No Study)	Jan. 1, 1996	
Corrosion Study and Treatment Recommendation (if Required by State)	July 1, 1996	Treatment Study Report and Results
State Approves/Designates Treatment (with Treatment)	Jan. 1, 1997	
Certification that the State-approved treatment has been installed		
Without Study	Jan. 1, 1998	Letter of Certification
With Study	Jan. 1, 1999	Letter of Certification
First Six-Month Follow-Up Monitoring Period Results ***		Form 141-A and Monitoring Results:
Without Study	July 11, 1998	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	July 11, 1999	Pb/Cu-TAP; WQP-DIS; WQP-POE
Second Six-Month Follow-Up Monitoring Period Results		Form 141-A and Monitoring Results:
Without Study	Jan. 11, 1999	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	Jan. 11, 2000	Pb/Cu-TAP; WQP-DIS; WQP-POE
State Specifies Optimal Water Quality Parameters		Based on Follow-Up Monitoring Results
Without Study	July 1, 1999	
With Study	July 1, 2000	
First Six-Month Monitoring Period Results after State Specifies Optimal WQP — Routine Monitoring		Form 141-A and Monitoring Results:
Without Study	Jan. 11, 2000	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	Jan. 11, 2001	Pb/Cu-TAP; WQP-DIS; WQP-POE



## REGULATORY REQUIREMENTS FOR STUDIES

**Table 2-2. Timeline for Small PWSs to Comply with the Corrosion Control and Source Water Treatment Requirements\* (continued)**

PWS Action	Date	Submission to State
Second Six-Month Monitoring Period Results after State Specifies Optimal WQP — Routine Monitoring		Form 141-A and Monitoring Results:
Without Study	July 11, 2000	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	July 11, 2001	Pb/Cu-TAP; WQP-DIS; WQP-POE Form 141-B when State-specified WQPs have been maintained for two consecutive six-month monitoring periods
Reduced Monitoring	See Appendix A of Volume I for Dates	Form 141-A and Monitoring Results: Pb/Cu-TAP; WQP-DIS; WQP-POE Form 141-B when State-specified WQPs maintained for three consecutive years under reduced monitoring
Ultimate Reduced Monitoring	See Appendix A of Volume I for Dates	Form 141-A and Monitoring Results Pb/Cu-TAP; WQP-DIS; WQP-POE

\* Specifically for those small PWSs which exceed the ALs and are required to implement corrosion control treatment and must meet State-specified WQPs.

If a small PWS does not exceed the ALs in the two consecutive monitoring periods, then they may request reduced monitoring (Form 141-B) when submitting results of the second six-month monitoring period. Those systems that meet the ALs are only required to submit Form 141-A and Pb/Cu-TAP monitoring results under reduced monitoring.

\*\* PWSs that meet the ALs in the first six-month round of initial monitoring and fail in the second six-month monitoring period would submit Form 141-A with Pb/Cu-TAP results on January 11, 1993, and submit Form 141-A with Pb/Cu-TAP, WQP-DIS, WQP-POE, Pb/Cu-POE results on July 11, 1993. All other deadlines shown in Table 2-2 should be delayed by six months.

\*\*\* PWSs that meet the ALs in the first six-month period and fail to meet the ALs in the second six-month period of the follow-up monitoring only need to submit Pb/Cu-TAP results for the first six-month period of follow-up monitoring.

## REGULATORY REQUIREMENTS FOR STUDIES

**Table 2-3. Timeline for Medium-Size PWSs to Comply with the Corrosion Control and Source Water Treatment Requirements\***

PWS Action	Date	Submission to State
First Six-Month Initial Monitoring Period Results** • Exceed ALs	Jan. 11, 1993	Form 141-A and Monitoring Results: Pb/Cu-TAP; WQP-DIS; WQP-POE
Desk-Top Treatment Evaluation Begins	Jan. 1, 1993	
Source Water Monitoring Results	July 1, 1993	Pb/Cu-POE
Treatment Recommendation	July 1, 1993	Treatment recommendations for corrosion control and/or source water treatment
State Requires Corrosion Studies	Jan. 1, 1994	As necessary, State notifies PWSs required to perform corrosion studies
State Approves/Designates Treatment (No Study)	July 1, 1994	
Corrosion Study and Treatment Recommendation (if Required by State)	July 1, 1995	Treatment Study Report and Results as Discussed in Volume II
State Approves/Designates Treatment (with Treatment)	Jan. 1, 1996	
Certification that the State-designated treatment has been installed		
Without Study	July 1, 1996	Letter of Certification
With Study	Jan. 1, 1998	Letter of Certification
First Six-Month Follow-Up Monitoring Period Results ***		Form 141-A and Monitoring Results:
Without Study	Jan. 11, 1997	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	July 11, 1998	Pb/Cu-TAP; WQP-DIS; WQP-POE
Second Six-Month Follow-Up Monitoring Period Results		Form 141-A and Monitoring Results:
Without Study	July 11, 1997	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	Jan. 11, 1999	Pb/Cu-TAP; WQP-DIS; WQP-POE
State Specifies Optimal Water Quality Parameters		Based on Follow-Up Monitoring Results
Without Study	Jan. 1, 1998	
With Study	July 1, 1999	
First Six-Month Monitoring Period Results after State Specifies Optimal WQP — Routine Monitoring		Form 141-A and Monitoring Results:
Without Study	July 11, 1998	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	Jan. 11, 2000	Pb/Cu-TAP; WQP-DIS; WQP-POE

## REGULATORY REQUIREMENTS FOR STUDIES

**Table 2-3. Timeline for Medium-Size PWSs to Comply with the Corrosion Control and Source Water Treatment Requirements\* (continued)**

PWS Action	Date	Submission to State
Second Six-Month Monitoring Period Results after State Specifies Optimal WQP — Routine Monitoring		Form 141-A and Monitoring Results:
Without Study	Jan. 11, 1999	Pb/Cu-TAP; WQP-DIS; WQP-POE
With Study	July 11, 2000	Pb/Cu-TAP; WQP-DIS; WQP-POE Form 141-B when State-specified WQPs have been maintained for two consecutive six-month monitoring periods
Reduced Monitoring	See Appendix A of Volume I for Dates	Form 141-A and Monitoring Results: Pb/Cu-TAP; WQP-DIS; WQP-POE Form 141-B when State-specified WQPs maintained for three consecutive years under reduced monitoring
Ultimate Reduced Monitoring	See Appendix A of Volume I for Dates	Form 141-A and Monitoring Results Pb/Cu-TAP; WQP-DIS; WQP-POE

\* Specifically for those small PWSs which exceed the ALs and are required to implement corrosion control treatment and must meet State-specified WQPs.

If a small PWS does not exceed the ALs in the two consecutive monitoring periods, then they may request reduced monitoring (Form 141-B) when submitting results of the second six-month monitoring period. Those systems that meet the ALs are only required to submit Form 141-A and Pb/Cu-TAP monitoring results under reduced monitoring.

\*\* PWSs that meet the ALs in the first six-month round of initial monitoring and fail in the second six-month monitoring period would submit Form 141-A with Pb/Cu-TAP results on January 11, 1993, and submit Form 141-A with Pb/Cu-TAP, WQP-DIS, WQP-POE, Pb/Cu-POE results on July 11, 1993. All other deadlines shown in Table 2-2 should be delayed by six months.

\*\*\* PWSs that meet the ALs in the first six-month period and fail to meet the ALs in the second six-month period of the follow-up monitoring only need to submit Pb/Cu-TAP results for the first six-month period of follow-up monitoring.

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Large PWSs performing demonstration testing, for example, may provide the States and small/medium-size PWSs with relevant experiences and findings for defining optimal corrosion control treatment. Small and medium-size systems that want to incorporate demonstration testing results from another PWS must submit recommendations to the State within six-months of exceeding an AL that includes:

- 1) the rationale supporting the need for additional information to make a final recommendation for corrosion control treatment;
- 2) the identity of the PWS performing demonstration testing;
- 3) the comparability of the small or medium-size PWS's water quality to that of the system performing the demonstration testing;
- 4) the feasibility for the small/medium-size PWS to implement the alternative treatments under investigation in the demonstration testing program; and,
- 5) the small/medium-size PWS's willingness to implement the recommendations resulting from the on-going demonstration testing program.

For those systems performing their own corrosion control demonstration testing program, information is presented in Chapter 4 of this Guidance Manual on how to develop and conduct such a study.

States have six months to review the recommendations of PWSs regarding optimal treatment or the requirement for additional testing, and either approve the selected treatment option or else designate an alternative treatment for installation. PWSs have two years in which to install and start up the approved treatment

alternative on a full-scale basis. At this point, follow-up monitoring is to be performed and compliance with the LCR rests with the ability of the PWS to properly operate the installed treatment.

### ***2.2.2 State Actions and Decisions.***

State activity in implementing the LCR requires decision-making, PWS notification, monitoring and reporting of compliance status, and oversight of PWS actions.

**2.2.2.1 Review of recommended treatment.** Small and medium-size PWSs which submit recommendations for optimal treatment should provide the checklist and Form 141-C for State review. If insufficient information is made available by the PWS, the State may request any additional data necessary to complete the assessment of the recommendations. Twelve months are provided for States to review submittals from medium-size PWSs, and 18 months are provided for small system recommendation review. Acceptance of the recommended treatment may be granted by the State or else optimal treatment must be designated for systems to install.

Small and medium-size systems are not required to conduct demonstration testing (static, flow-through, or full-scale) before making their recommendations for optimal corrosion treatment. However, any PWS that does not conduct a thorough evaluation of its treatment recommendation must realize the risks involved. A desk-top evaluation considers alternatives based on the experience of other PWSs and product manufacturers' recommendations. As each PWS has a unique supply,

## REGULATORY REQUIREMENTS FOR STUDIES

treatment, and distribution system, assurance that the recommended treatment will be effective is lacking without actual demonstration testing. Small and medium-size PWSs may recommend that the findings from a comparable system performing demonstration testing be incorporated into the evaluation of their system; thereby providing an opportunity for these systems to utilize the results of relevant testing programs in the selection of optimal treatment. However, studies which utilize static testing and flow-through testing procedures do not automatically insure that the selected process will provide satisfactory results when implemented full scale. Each PWS must carefully review its individual situation before deciding which approach is most appropriate for its particular set of circumstances.

In reviewing the submittals, several features of the checklist and Form 141-C may assist the States in determining the appropriateness of the recommended treatment. Namely,

- Completeness of the information provided;
- Supporting documentation regarding the experiences of the PWS or other, comparable PWSs with alternative corrosion control treatment approaches;
- Consistency with the desk-top evaluation procedures described in the Guidance Manual; and,
- Evidence of the PWS's general understanding of the alternative treatment methods and their application.

A primary concern for States will be the appropriate use of treatment products in order that successful corrosion control

programs may be implemented by small and medium-size PWSs.

**2.2.2.2 Requirement for additional study.** PWSs are to be notified within six months of submitting recommendations for optimal treatment that a corrosion control study is required by the State. Certain small or medium-size PWSs may desire to perform corrosion control studies in order to more fully evaluate the alternative treatment processes. If this is the case, then these PWSs should submit recommendations for the alternatives to be included in the demonstration testing to the State within six months of exceeding the AL in lieu of recommendations for optimal treatment. This will provide an additional six-month period for performing the demonstration study. Those systems wishing to incorporate the findings of a comparable system performing demonstration testing should include the five items presented in Section 2.2.1 in their submittal to the State. If the State approves this recommendation, the PWS would have an additional 18-months to present final recommendations for optimal treatment, documenting the incorporation of the findings from the demonstration testing performed by the relevant system.

**2.2.2.3 Designating alternative treatment.** States have the authority to designate treatment for small and medium-size PWSs which have exceeded the ALs and submitted recommendations for optimal treatment. However, it is recommended that States and PWSs mutually determine optimal treatment in cases where the recommended approach appears to be questionable by the State. Additionally, States could require demonstration

## REGULATORY REQUIREMENTS FOR STUDIES

testing when significant uncertainty regarding the performance of alternative treatments cannot be resolved through other means.

### 2.2.2.4 Notification requirements.

States have several notification steps relevant for small and medium-size PWSs exceeding ALs during initial monitoring. The dates and types of notification must be issued by States as part of the treatment requirements for the LCR are

presented in Table 2-4 for the case where an AL is exceeded during the first six-month period of initial monitoring.

## 2.3 References

USEPA. 1991. Technologies and Costs for the Removal of Lead and Copper from Potable Water Sources. Office of Ground Water and Drinking Water. (Washington, D.C.).

**Table 2-4. Dates for State Notification\***

Notification Action	Small PWSs	Medium-size PWSs
Requirement for Corrosion Control Studies	January 1995	January 1994
Source Water Treatment Approval/Disapproval	January 1995	January 1994
Corrosion Control Treatment Approval/Designation	July 1996	January 1995

\* These dates are based on the assumption that the water system exceeded an action level in the first six-month period of the initial monitoring. For those small and medium-size systems that meet the ALs in the first six-month period and fail in the second six-month period, the dates would be delayed by six months.

## Chapter 3.0 — Screening of Corrosion Control Alternatives

Many small and medium-size PWSs will be required to evaluate, select and implement optimal corrosion control treatment to meet lead and copper action levels (ALs). Additionally, most large PWSs will be required to perform corrosion control studies which includes desk-top evaluations of alternative treatment approaches. States will likewise be required to review the findings and recommendations of corrosion control investigations, and, in some cases, designate treatment for LCR compliance. To assist each in these endeavors, this Chapter provides:

- a discussion of the basic principles of corrosion and the available corrosion control treatment approaches;
- the steps necessary to develop treatment recommendations for small and medium systems exceeding an AL or large systems required to perform desk-top evaluations;
- a checklist for small and medium-size PWSs and States to use in evaluating the selected treatment; and
- several case studies illustrating the procedure and rationale used to perform desk-top evaluations.

References are also provided for those seeking more detailed and rigorous presentations on this subject.

### ***3.1 Principles of Corrosion and Corrosion Control***

Corrosion causes the deterioration of crystalline structures that form the pipe materials, and can occur by one of three principle mechanisms: abrasion, metabolic activity, and dissolution. Abrasion is the physical removal of pipe material due to irregularities in the pipe surface which may dislodge under high fluid velocities. Metabolic activity refers to the utilization of pipe materials as a nutrient supply by microorganisms. The dissolution of pipe materials occurs when favorable water chemistry and physical conditions combine, generating the following possible corrosion scenarios:

- *Uniform Corrosion* - when the water freely dissolves metals from the pipe surface;
- *Concentration Cell Corrosion* - when anodic and cathodic points are established along the pipe surface, causing the sacrifice of metals at the anode (dissolved metal species) and the re-precipitation of less soluble metal compounds at the cathode.
- *Galvanic Corrosion* - when two dissimilar metals are in contact with each other, accelerating the dissolution of the material with the greater tendency to corrode.



## SCREENING OF ALTERNATIVES

Corrosion of drinking water distribution systems can result from any of the above mechanisms or combinations of the various types of corrosion activity as illustrated in Figure 3-1. Alteration of water quality characteristics via treatment can extensively reduce some forms of corrosion activity, but may have a less significant affect on others (AWWARF/DVGH, 1985).

Corrosion control treatment is principally intended to inhibit dissolution. The objective is to alter the water quality such that the chemical reactions between the water supply and the pipe materials favor the formation of a protective layer on the interior of the pipe walls. Corrosion control treatment attempts to reduce the contact between the pipe and the water by creating a film that is: (1) present throughout the distribution and home plumbing systems; (2) relatively impermeable; (3) resistant to abrupt changes in velocity and/or flow direction; and (4) less soluble than the pipe material (Neff, 1991).

Coincidental reductions of other corrosion activity may be accomplished when dissolution of lead and copper are minimized. Abrasion of piping materials is typically accelerated when corrosion byproducts, such as tubercles, are present in the distribution system. Abrasion activity normally diminishes when tubercles are reduced or if the tubercles can be coated with a less permeable substance. This effect has been noted by several full-scale systems which have reported fewer customer complaints about red or black water events after corrosion control treatment was implemented.

Most researchers agree that implementing corrosion control will alter the finished water chemistry which subsequently may

influence microbial growths within the distribution system. Recent studies have shown that biofilms are strongly associated with corrosion byproducts within distribution systems (Allen, et al., 1980; Herson, et al., 1991; AWWARF, 1990a). This association makes the biofilms more resistant to disinfection, and therefore, more persistent when active corrosion takes place in distribution system piping. While biofilm formation may be promoted by corrosion, it remains difficult to accurately quantify the effects of microbial activity on corrosion rates in distribution systems and the effect of treatment on such activity.

Some PWSs have also experienced increases in distribution system microbial growth when corrosion control treatment was implemented due to the addition of nutrients (phosphorus, inorganic carbon, silica) to the finished water. In particular, this may become a problem within distribution systems where chloramines are used for final disinfection and a phosphorus-based inhibitor is applied for corrosion control. As chloramines are reduced during oxidation, ammonia (a potential nitrogen source) is released into the water. Thus the presence of two major nutrients, nitrogen and phosphorus, could increase microbial growth. This is especially likely in the extremes of the distribution system where localized areas with inadequate disinfectant may occur (Hoehn, 1991).

Algal growth may also occur in uncovered distribution system reservoirs. The primary nutrients necessary for algae to proliferate are nitrogen and phosphorus. Phosphorus tends to be the controlling nutrient as some algal species are able to obtain nitrogen from the atmosphere for

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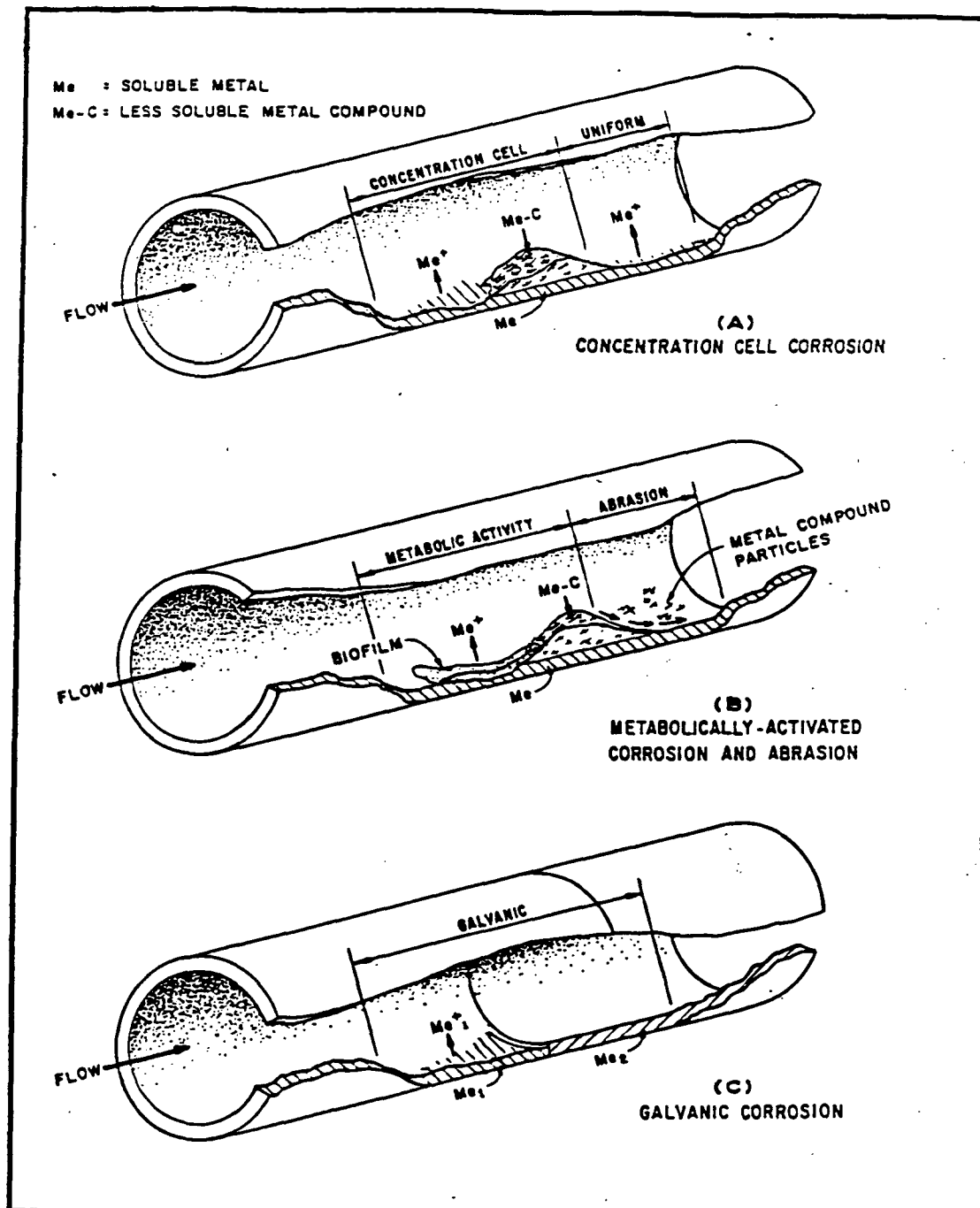


Figure 3-1. Forms of Corrosion Activity Encountered in Potable Water Distribution Systems

their metabolic processes. Thus, the use of a phosphate-based inhibitor may promote unwanted algal growth in some systems. In the early 1980s a state agency, the Metropolitan District Commission (MDC), was responsible for supplying water to the Boston metropolitan area. One reason that MDC chose to discontinue feeding a zinc orthophosphate inhibitor for corrosion control was the possibility that the phosphate was responsible for increased algal growth in the distribution system reservoirs (Karalekas, et al., 1983).

### 3.2 Corrosion Control Treatment Alternatives

As illustrated in Table 3-1, available corrosion control technologies can be characterized by two general approaches to inhibiting lead and copper dissolution: (1) forming a precipitate in the potable supply which deposits onto the pipe wall to create a protective coating; or (2) causing the pipe material and the potable supply to interact in such a way that metal compounds are formed on the pipe surface, creating a film of less soluble material. The difference in these two approaches is the mechanism by which the protective film is formed. In the former method, insoluble compounds are formed by adjusting the water chemistry to cause the **precipitation** of the compound onto the pipe wall. The success of this method is dependent on: (a) the ability to form precipitates in the water column, and (b) the characteristics of the deposit on pipe walls, including its permeability, adherence strength, and uniformity. In the latter approach, the mechanism is the **passivation** of the pipe material itself through the formation of less soluble metal com-

pounds (carbonates or phosphates) which adhere to the pipe wall. In the case of non-metallic pipe materials, such as asbestos-cement (AC) pipe, passivation and precipitation mechanisms are also operative. The calcium present in the AC pipe acts as the metallic component, being available to react with the carbonate or phosphate species under passivating conditions. Various chemical treatment practices are available to promote precipitation and/or passivation in PWSs. The most effective corrosion control treatment may actually rely on some combination of these two mechanisms (AWWARF/DVGM, 1985; AWWARF, 1991; Kirmeyer and Logsdon, 1983; AWWARF, 1990b).

In general, the available corrosion control treatment technologies are:

- **Alkalinity and pH Adjustment**, which refers to the modification of pH and/or alkalinity (as a surrogate for dissolved inorganic carbonate) to induce the formation of less soluble compounds with the targeted pipe materials. This method utilizes *passivation* as the mechanism for corrosion control.
- **Calcium Hardness Adjustment**, which refers to the adjustment of the calcium-carbonate system equilibrium such that a tendency for calcium carbonate precipitation results. This method of corrosion control depends upon *precipitation* as the means of protecting piping systems. The term "calcium hardness adjustment", in many cases, may be a misnomer since calcium addition or reduction may not be required. Instead, modifying the pH and/or alkalinity through treatment may be the mechanism for achieving a tendency for calcium carbonate precipitation.

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**Table 3-1. Conceptual Framework for Corrosion Control Approaches**

Control mechanism	→	Passivation		Precipitation
Treatment Approach	→	pH/Alkalinity Adjustment	Corrosion Inhibitor	Calcium Adjustment
Key Water Quality Parameters	→	pH, Alkalinity, TDS, Temperature	pH, Alkalinity, Metals, Hardness, Temperature	Calcium, pH, Alkalinity, TDS, Temperature
Appropriate Chemical Feed Systems	→	Lime Soda Ash Sodium Bicarbonate Caustic Soda Carbon Dioxide	Orthophosphate Silicates Polyphosphate Ortho-Polyphosphate	Lime Soda Ash Sodium Bicarbonate Caustic Soda Carbon Dioxide

- **Corrosion Inhibitors**, which refers to the application of specially formulated chemicals characterized by their ability to form metal complexes and thereby reduce corrosion. This method employs *passivation* of the metal surface as the means of corrosion control. The common corrosion inhibitors generally available include orthophosphate, polyphosphates, poly-orthophosphate blends, and silicates.

Each of these treatment techniques is discussed more extensively in the following sections.

### 3.2.1 Alkalinity and pH Adjustment.

The solubility of metals is dependent on the specie in which that metal is found. Elemental lead and copper will form complexes with such chemical groups as the hydroxyl ( $\text{OH}$ ), carbonate ( $\text{CO}_3$ ), bicarbonate ( $\text{HCO}_3$ ), orthophosphate ( $\text{PO}_4$ ), and silicate ( $\text{SiO}_2$ ). The pH/alkalinity adjustment method relies upon the formation of less soluble metal species consisting of hydroxyl-carbonate compounds.

Figures 3-2 and 3-3 present an example of the family of solubility contour diagrams for lead and copper, respectively, which are derived for various temperature and ionic strength conditions. These particular contour diagrams are based on the theoretical solubility of various metal hydroxy-carbonate species for a water with moderately low total dissolved solids (200 mg/L TDS = 0.005 Ionic strength) and temperature of 25 °C. To read the chart, the x-axis is the dissolved inorganic carbonate (DIC) content, and the y-axis is the pH of the

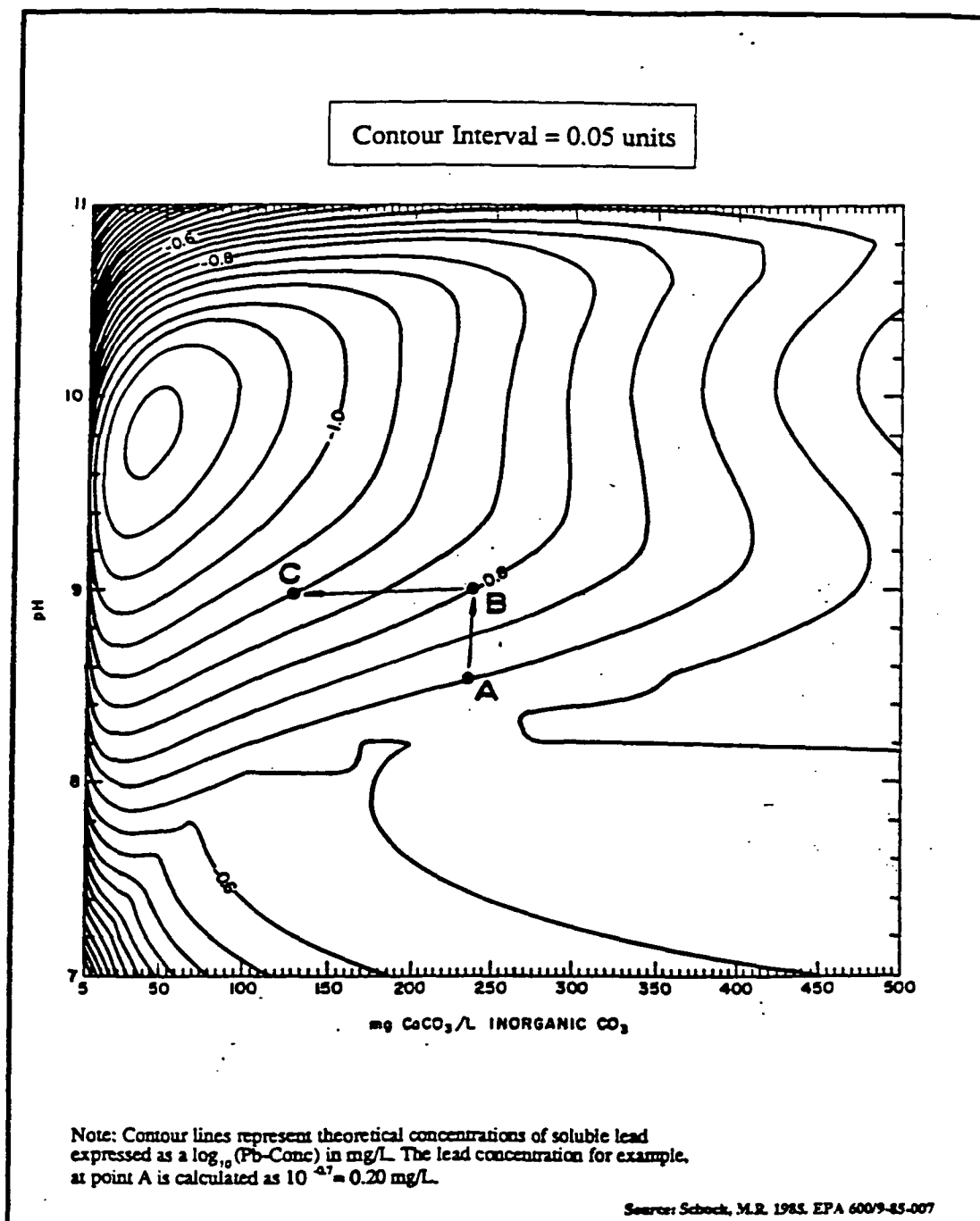
treated water. A chart to convert total alkalinity to DIC is provided in Table A-2 of Appendix A. For a particular pH and DIC, the theoretical lead solubility, for example at point A in Figure 3-2, would be  $10^{-0.7} = 0.20$  mg/L lead. By increasing the pH alone to pH = 9 (point B) the lead solubility would decrease to  $10^{-0.80} = 0.16$  mg/L. If the DIC content were reduced as well (moving from point B to point C on Figure 3-2), the theoretical lead solubility is further reduced to  $10^{-0.90} = 0.13$  mg/L.

As Figure 3-2 illustrates, the minimum lead solubility occurs at relatively high pH conditions (pH 9.8) and low alkalinity (30-50 mg/L as  $\text{CaCO}_3$  for DIC). Similar pH and alkalinity conditions provide minimum solubility for copper as shown in Figure 3-3. However, copper solubility appears to be more strongly related to pH than alkalinity.

These types of figures may be used to assess the potential value of applying a pH/alkalinity adjustment treatment technique for particular supplies. Alternative water quality goals - consisting of modified pH and alkalinity conditions - may be evaluated by determining the estimated reduction in theoretical lead and copper solubility. The approach which should be considered a candidate is able to: (1) maximize the relative reduction in lead and copper solubility with respect to the existing treatment, and (2) meet all other treatment objectives at the least cost.

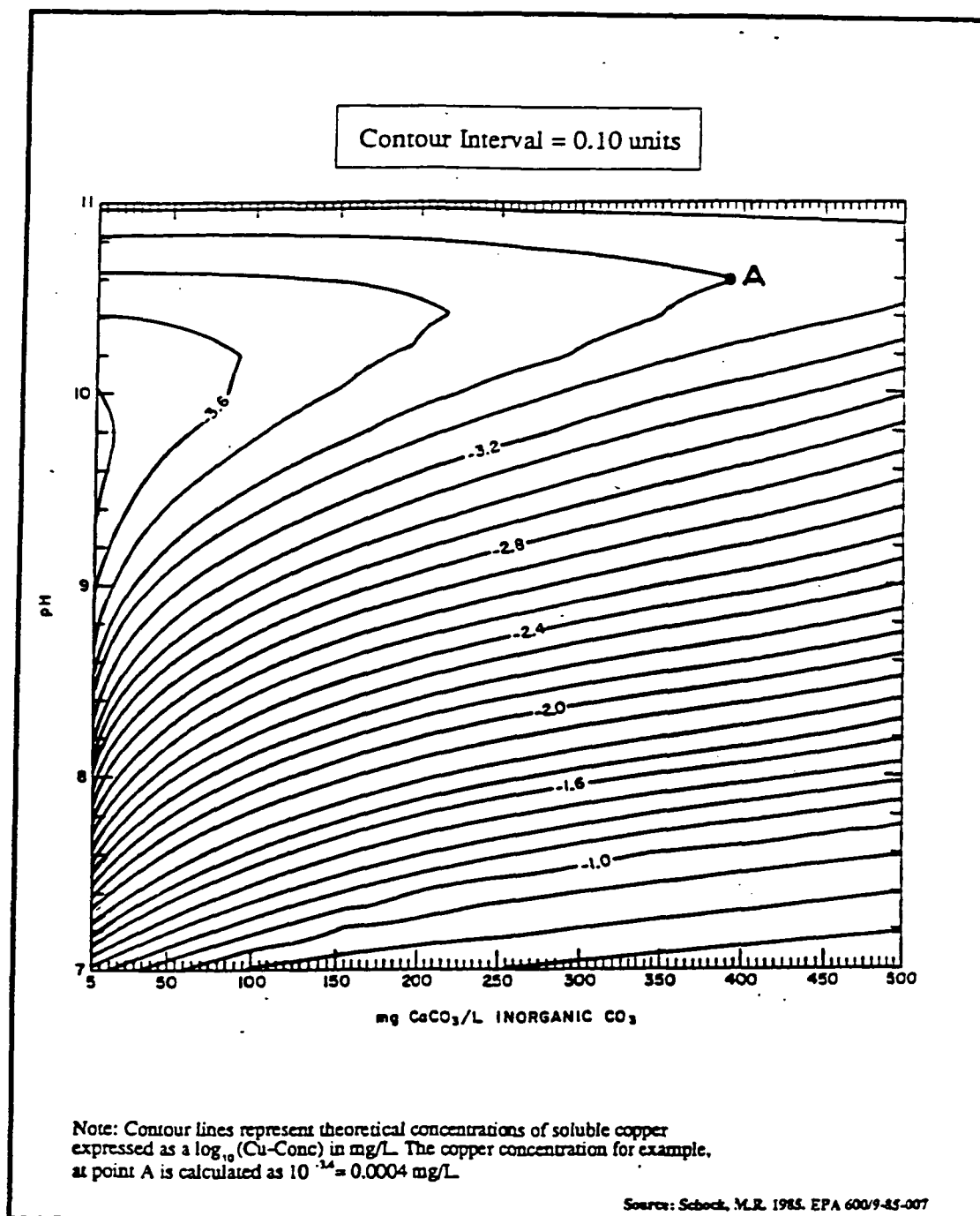
The chemical feed systems which may be installed to modify pH and alkalinity conditions in the finished water are summarized in Table 3-2. Many of the chemicals shown in Table 3-2 will both increase the pH and the alkalinity of the finished water. In some cases,

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**Figure 3-2. Contour Diagram of Lead (II) Solubility in the System Lead (II)-Water-Carbonate at 25°C and an Ionic Strength of 0.005 mol/L**

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**Figure 3-3. Contour Diagram of Copper (II) Solubility in the System Copper (II)-Water-Carbonate at 25°C and an Ionic Strength of 0.005 mol/L**

**Table 3-2. Summary of Chemicals Typically Used in pH/Alkalinity and Calcium Adjustment Corrosion Control Treatment**

Chemical	Use	Composition	Alkalinity Change	Notes
Caustic Soda, NaOH	Raise pH. Convert excess CO <sub>2</sub> to alkalinity species	93% purity liquid bulk. Colder climates, bulk storage at <50% purity to prevent freezing	1.55 mg/L CaCO <sub>3</sub> alkalinity per mg/L as NaOH	pH control is difficult when applied to poorly buffered water
Lime, Ca(OH) <sub>2</sub>	Raise pH. Increases alkalinity and calcium content	95-98% purity as Ca(OH) <sub>2</sub> . 74% Active ingredient as CaO. Dry storage with slurry feed	1.21 mg/L CaCO <sub>3</sub> alkalinity per mg/L as Ca(OH) <sub>2</sub>	pH control is difficult when applied to poorly buffered water. Slurry feed can cause excess turbidity. O&M intensive
Sodium Bicarbonate, NaHCO <sub>3</sub>	Increases alkalinity with little increase in pH	98% purity. Dry storage with solution feed	0.60 mg/L CaCO <sub>3</sub> alkalinity per mg/L as NaHCO <sub>3</sub>	Good alkalinity adjustment choice, but very expensive
Soda Ash, Na <sub>2</sub> CO <sub>3</sub>	Increases alkalinity with moderate increase in pH	95% purity. Dry storage with solution feed	0.90 mg/L CaCO <sub>3</sub> alkalinity per mg/L as Na <sub>2</sub> HCO <sub>3</sub>	More pH increase caused as compared to NaHCO <sub>3</sub> , but less costly
Carbon Dioxide, CO <sub>2</sub>	Lowers pH. Converts excess hydroxyls to bicarbonate and carbonate species	Pressurized gas storage. Fed either through eduction or directly	None	Can be used to enhance NaOH or lime feed systems



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combinations of the available chemical feed systems are more appropriate to ensure that pH and alkalinity goals may be met simultaneously. This is especially important in poorly buffered systems where pH adjustment alone through the use of either caustic soda or lime, for example, could cause unacceptably elevated pH levels or erratic pH levels in the treated water and within the distribution system. In these cases, the use of sodium bicarbonate or carbon dioxide may be used in conjunction with the lime or caustic soda system to provide additional buffering capacity.

Apart from those chemical applications shown in Table 3-2, other treatment processes may affect the pH/alkalinity of the finished water; namely, aeration, alum coagulation, chlorination and fluoridation. These additional sources of pH and alkalinity impacts must be incorporated into the comprehensive treatment design in order to successfully achieve the recommended finished water quality goals for pH and alkalinity.

The operation of a full-scale facility using the pH/alkalinity modification approach should consider several factors in the design of the corrosion control program:

- the location of each chemical feed for optimal utilization, including coagulants, oxidants (such as chlorine), fluoride, and pH/alkalinity modification chemicals.
- monitoring locations for process control, whether manual or automatic;
- sequencing the control of chemical feed rates in order to reach all of the water quality goals while minimizing chemical usage; and,

- the available contact time and mixing conditions necessary to achieve a stable finished water prior to entry to the distribution system.

When determining the location of chemical feed points, the pH adjustment resulting from chemical additions must be considered. This is especially relevant for waters that are weakly buffered. Chlorine addition in the gaseous form, for example, will tend to lower the pH while adding chlorine in the hypochlorite form will tend to raise the pH. Likewise, both sodium silicofluoride and hydrofluosilicic acid which are commonly used in fluoridation are acidic and will tend to lower the pH. Adjustment of the finished water pH for corrosion control cannot be permitted to interfere with the objectives of other water treatment operations. Disinfection with free chlorine, for example, is more effective at lower pH values because the hypochlorous acid formed by the addition of chlorine converts rapidly to the hypochlorite ion above pH 7. Hypochlorite ion has long been known to be less effective as a biocide than hypochlorous acid. For instance, under the SWTR, higher CT values are required at higher pH levels to accomplish equivalent microbial inactivation.

### ***3.2.2 Calcium Adjustment.***

The formation of a calcium carbonate precipitate may be used to coat the interior walls of pipes and thereby reduce the corrosion of the pipe surface. The success of this treatment depends on delivering a finished water slightly supersaturated with calcium and carbonate (at a specified pH condition) such that calcium carbonate precipitation occurs. The availability of

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the supersaturated conditions throughout the distribution system and the reliability of existing techniques to predict the potential formation of calcium carbonate precipitates are key factors to providing corrosion control protection. Success also depends on the ability to control the formation of scale buildup to insure that hydraulic capacity is not unduly sacrificed in the course of providing corrosion protection.

The calcium-carbonate equilibrium is a dynamic system which will change continuously from the point of entry to the final service connection throughout the distribution system. Achieving a continuous coating of calcium carbonate precipitate is difficult without causing excessive precipitation in some portions of the system. This can result in significant reductions to the supply capacity of the distribution system, especially in the vicinity of the treatment plant, and require those lines to be cleaned in order to reestablish the necessary hydraulic conditions.

The complications associated with calcium adjustment are increased by the difficulties in precisely determining the degree of calcium carbonate precipitation in the treated water. Several indices have been proposed to describe the calcium-carbonate equilibrium, and the tendency of water to form precipitates. PWSs should exercise caution, however, when using traditional indices to predict performance for lead and copper control. Such indices may not be adequate to predict the performance of the calcium adjustment approach, although they may be useful to *initially* estimate the water quality conditions necessary to precipitate calcium

carbonate. The Calcium Carbonate Precipitation Potential (CCPP) index may be the most useful for this purpose. A more detailed description of the CCPP and its method of calculation is provided in Appendix A.

To understand and effectively utilize any of the indices discussed in Appendix A, or to derive calcium carbonate saturation conditions without the use of indices, it is necessary to review the calcium-carbonate equilibrium system. Figure 3-4 presents the solubility diagram for calcium carbonate as a function of pH under "closed system" conditions, i.e., no exchange of carbonate species ( $\text{CO}_2$ ) is permitted between the water and air systems. Open systems could involve the dissolving and de-gassing of carbon dioxide, which would affect calcium carbonate solubility. As the pH increases, the solubility of calcium carbonate decreases such that more calcium carbonate will precipitate rather than stay in solution. However, these reactions are not instantaneous, and therefore, sufficient time must be provided within the targeted pH range for precipitation to occur. For example, lime softening plants which have excess calcium carbonate present after softening often re-carbonate the clarified water (reduce the pH) prior to filtration. This increases the solubility of calcium and prevents the filter media from becoming coated with calcium carbonate precipitates which otherwise would continue to form under the elevated pH conditions.

The water treatment goals for this approach should include the pH, carbonate content (alkalinity) and calcium concentrations necessary to achieve calcium carbonate precipitation. The chemical feed

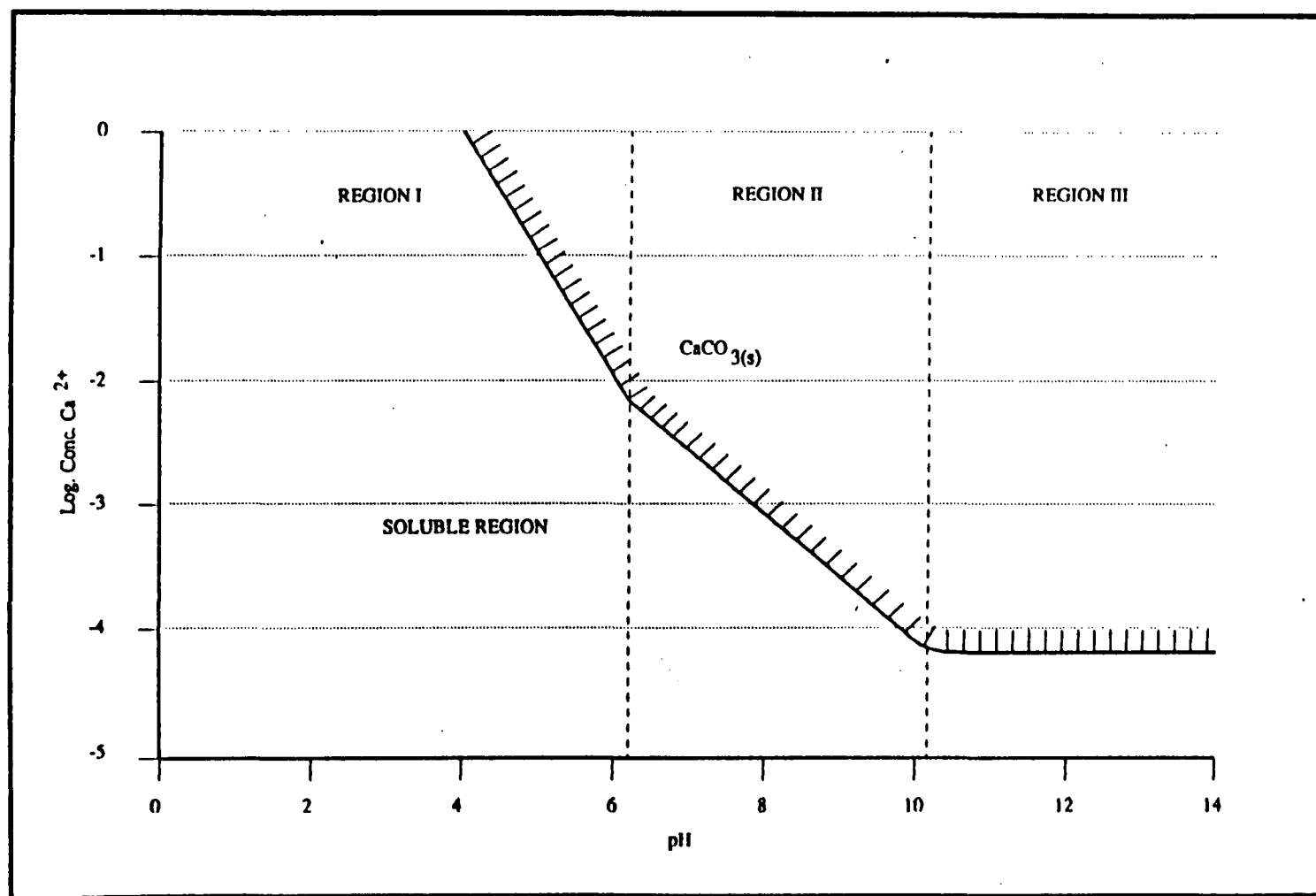


Figure 3-4. Solubility Diagram for Calcium Carbonate in a Closed System at 25°C

systems which may be used to implement calcium adjustment treatment are summarized in Table 3-2. Many of these chemicals are applicable in the pH/alkalinity adjustment approach, but the finished water quality goals would differ.

### **3.2.3 Corrosion Inhibitors.**

Two predominant forms of corrosion inhibitors are available for potable water treatment: phosphate and silicate-based compounds. Somewhat different chemical mechanisms of corrosion control and water quality criteria are associated with the effective use of phosphate and silicate-based inhibitors. However, both utilize passivation as the method of providing corrosion protection.

A plethora of corrosion inhibitor formulations are commercially available to PWSs, and caution must be used in the review and consideration of the alternative products. As a direct additive to drinking water supplies, corrosion inhibitors are subject in most states to the American National Standards Institute (ANSI)/National Sanitation Foundation (NSF) Health Effects Standard 60 for direct additives. Products must be certified or approved by the primacy agent prior to being used in treating potable supplies. PWSs should contact their State agency to determine: (1) whether the State has adopted the ANSI/NSF Standard 60 for direct additives, and (2) a list of the certifying agencies or certified products for corrosion control treatment.

**3.2.3.1 Phosphate inhibitors.** Lead forms at least one orthophosphate solid of low solubility under typical drinking water conditions, which can serve as the

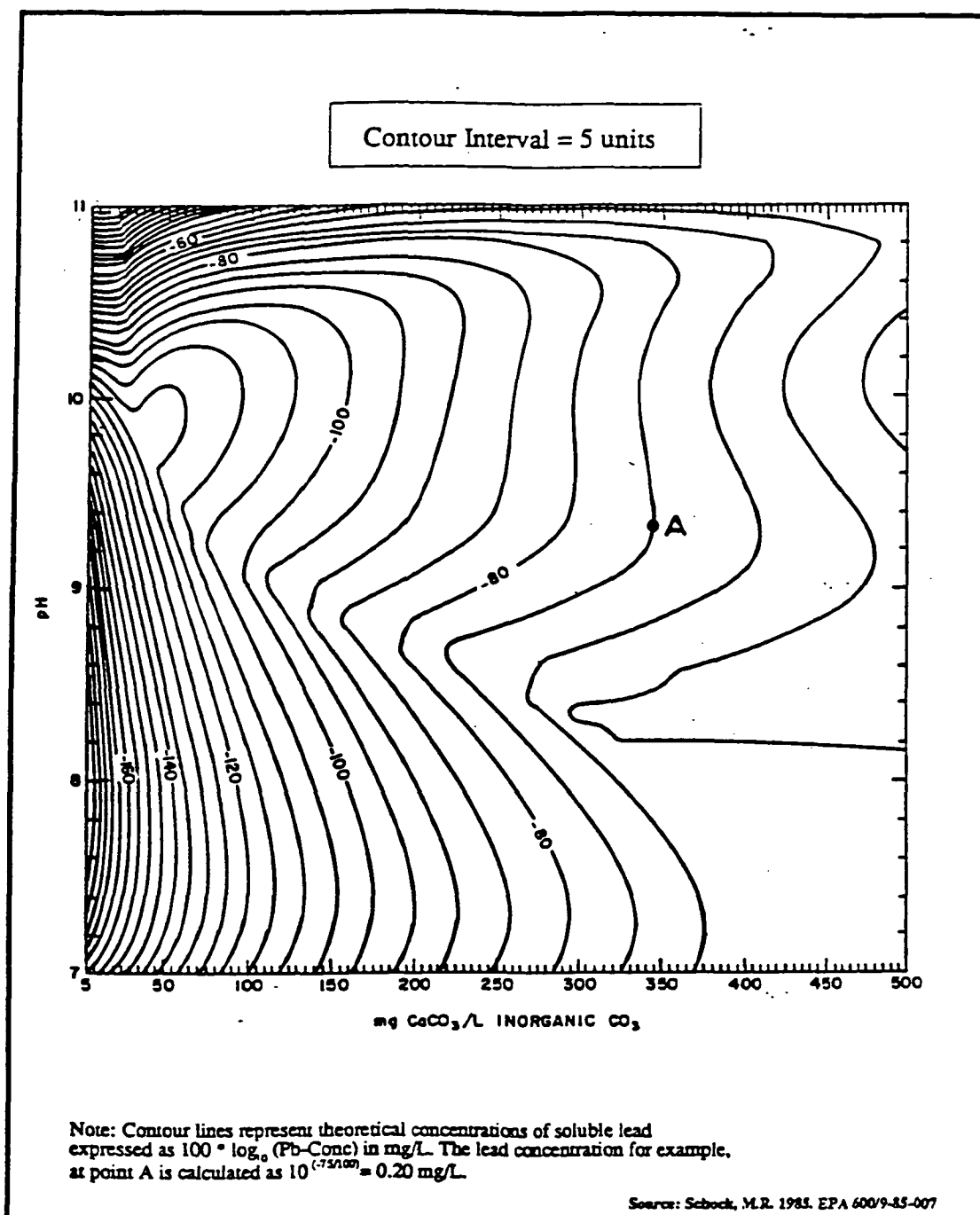
basis for corrosion control. Solubility contour diagrams like those presented for pH/alkalinity adjustment have been developed for lead when 0.5 mg/L  $\text{PO}_4$  is added to the finished water, as shown in Figure 3-5. The minimum theoretical lead solubility is reduced by approximately 0.5-logs with the addition of the orthophosphate, and the corresponding pH is much lower than that associated with the carbonate system alone.

Copper solubility does not appear to be markedly reduced by the inclusion of orthophosphate in solution until extremely high dosages are applied. The results of several corrosion studies using orthophosphate have found conflicting results with respect to their contribution to copper control (AWWARF, 1990b; Moser et al., 1992). Until additional insight can be garnered through additional research, testing should be performed to evaluate copper control by orthophosphate.

The pH range across which orthophosphate appears to be most effective for lead is 7.4 to 7.8 (AWWARF, 1990b; Lee et al., 1989; Lechner, 1991). At pH values much above 7.8, metal phosphate precipitates can form, causing scale buildup and hydraulic capacity losses. Waters with low hardness (calcium < 16 mg/L and a calcium to magnesium ratio of 0.7) are well-suited to the use of orthophosphate inhibitors.

The critical parameters to operating an orthophosphate corrosion control treatment program are: (1) maintaining a stable pH in the inhibitor's effective range throughout the distribution system; (2) determining the inhibitor composition best-suited for the specific water quality objectives and conditions; and (3) applying

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**Figure 3-5. Contour Diagram of Lead (II) Solubility in the Presence of 0.5 mg/L  $\text{PO}_4$  at 25°C and an Ionic Strength of 0.005 mol/L**

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the appropriate dosage to accommodate background orthophosphate demand as well as the corrosion control protection sought. Phosphate-based inhibitors are acidic solutions, and the pH effect of their addition to the finished water must be considered in determining the suitability of their application.

Since phosphates are effective over a constrained pH range, maintaining that range throughout the distribution system is an important component of implementing a successful corrosion control program. For systems which are well buffered, and whose pH is within the targeted range, this may not be a critical issue. However, for those PWSs with poorly buffered supplies (low alkalinity levels), pH fluctuations within the distribution system can be significant. For example, with a finished water alkalinity of less than 20 mg/L as  $\text{CaCO}_3$  and pH of 7.5, a PWS found distribution system pH values ranging from 6.5 to 9.0, depending on whether the water had passed through unlined ductile iron pipe, lined cast iron pipe, or asbestos-cement pipe. Such fluctuations in distribution system pH would adversely impact the performance of the corrosion inhibitor. Systems with poorly buffered water may have to install treatment to stabilize pH in addition to installing corrosion inhibitor systems for reducing lead and copper levels.

Thus, the use of inhibitors for corrosion control within the distribution system is analogous to maintaining a chlorine residual within the system as a safeguard against secondary contamination. Similar to the chlorine residual, the orthophosphate concentration must be sustained to be effective as a corrosion inhibitor

throughout the distribution system. However, unlike the chlorine residual which will inhibit biological functions at trace concentrations, the inhibitor must be carried above some minimum concentration to be useful. Because the composition of inhibitors vary and in some cases it is proprietary information, this minimum concentration should be determined in conjunction with the supplier.

Phosphate inhibitors are manufactured in a variety of compositions, including sodium orthophosphate, zinc orthophosphate, polyphosphates, and poly-orthophosphate blends. Each of these groups of compounds may have differing formulations as to the percentage of effective  $\text{PO}_4$  present. The selection of a specific inhibitor may require a preliminary evaluation of the following: (a) effectiveness in controlling lead and/or copper, (b) effects of depressing the final pH of the treated water, and (c) impacts on wastewater treatment facilities required to meet effluent standards for phosphorus.

Polyphosphates revert (hydrolyze) with time resulting in an increase in the orthophosphate ion. This reversion is affected by, among other parameters, pH, and available metal ions such as calcium and zinc. Because chemical suppliers provide proprietary inhibitors with formulations largely unknown to the user, it becomes essential that polyphosphate additives be tested under actual distribution system conditions. Testing for both orthophosphate and polyphosphate (see the hydrolyzable plus orthophosphate pathway in Figure 4-2, Lead and Copper Rule Guidance Manual, Volume I) should be monitored at the point of entry and throughout the distribution system. These

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data will assist in determining the correct inhibitor dose and in identifying and understanding the predominant mechanism of inhibition.

As Holm and Schock point out (Holm and Schock, 1991a; and Holm and Schock, 1991b), water treatment measures can sometimes unintentionally increase lead solubility. Products that contain polyphosphates can fall into this category. Holm and Schock refer to other research to support their conclusions regarding polyphosphates (Bailey, 1982; Sheiham and Jackson, 1981; Neff, et al., 1987; and Maas, et al., 1991). It is noteworthy that some researchers disagree with Holm and Schock, because some of this supporting research has restrictions which narrow their application. Nevertheless, EPA believes that polyphosphates should be used with caution because: "Applying chemicals whose effects are not well understood may be viewed in the extreme sense as an uncontrolled toxicological experiment on the general population. We feel this is the true disservice to the water utility industry" (Holm and Schock, 1991b).

Polyphosphates are not recommended for corrosion control purposes in general, although their application may be beneficial, if not required, for other water quality, operational, or treatment concerns. The principle use of such chemicals is to sequester dissolved metal or cationic constituents - such as calcium, iron, or manganese - and reduce their ability to precipitate either in the distribution system or within the water treatment plant. In the case of calcium, polyphosphates are used in many softening plants to minimize the encrustation of filter media by post-precipitation of calcium

carbonate. For iron and manganese control, polyphosphates can effectively reduce the aesthetic discoloration caused by these compounds. This is often a useful and necessary benefit of their application, particularly for groundwater systems which are heavily mineralized and devoid of oxygen, ideal conditions for iron and manganese to solubilize. Seasonally high levels of iron and manganese can also occur with surface water supplies when low dissolved oxygen and reducing conditions in upstream reservoirs increase the concentration of these minerals.

While polyphosphates have demonstrated limited direct success toward lead and copper corrosion control, their use at water treatment facilities will be necessary in many instances. Ortho-polyphosphate blends are being produced which may be able to offer some of the benefits of both uses to PWSs. These should be considered when orthophosphate inhibitors are a viable corrosion control approach, but a polyphosphate is also required to meet other treatment objectives.

Additionally, the proper application rate for a specific inhibitor should be determined through testing. As a preliminary assessment, the necessary dosage should include the phosphate-demand exerted by the water quality constituents present in the finished water. Beyond the dosage required for effective lead and/or copper control, metals present in the supply will combine with phosphates to differing degrees, imposing an effective "phosphate-demand" in the following order of preferential sequence (shown as: maximum ——— > minimum; or equivalent < ——— > equivalent) (Lechner, 1991).

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### I. Highest Demand

Manganese ——— >Iron ——— >Copper ——— >Aluminum ——— >Zinc/Lead

### II. Moderate Demand

Calcium< ——— >Magnesium< ——— >Barium< ——— >Radium

### III. Lowest Demand

Sodium< ——— >Potassium

The final dosage required should be sufficient to accommodate the phosphate-demand and provide the effective inhibitor residual necessary to achieve lead and/or copper corrosion control.

**3.2.3.2 Silicate inhibitors.** The mechanism involved in controlling corrosion is unclear for silicate applications. Silicates are manufactured by the fusion of high-quality silica sands to sodium or potassium salts. Sodium silicates are generally most common with sodium carbonate being used as the bonding salt. Conventional sodium silicates use silica to  $\text{Na}_2\text{CO}_3$  molar ratios between 1.5 and 4 to 1.

The most common form of silicate in water treatment is the 3.22 weight ratio sodium silicates at 41 °Baume' solution with 37-38 percent solids. This has been used successfully for corrosion control treatment when targeting reductions in iron corrosion. For lower pH waters, a more alkaline silicate product may be appropriate, such as the weight ratio 2.00  $\text{Si}_2\text{O}:\text{Na}_2\text{O}$  with 50.5 °Baume' solution to reduce acidity and increase the overall buffering capacity of the water.

The method of controlling corrosion attributed to silicates appears to be a combination of adsorption and formation of less soluble metal-silicate compounds.

Silicates are considered anodic inhibitors, combining with the free metal released at the anode site of corrosion activity and forming an insoluble metal-silicate compound. These corrosion products crystallize to form a protective barrier on the face of pipe walls. However, microscopic and X-ray examinations have shown two layers of film on iron pipes conveying water treated with silicates. The majority of the silicate appears in the uppermost layer adjacent to the water. This film is an amorphous silicate film adhered to the underlying silicate-metal surface. A slightly corroded surface may be necessary to form the protective silicate film. Simultaneously, the application of silicates in a distribution system with extensive corrosion byproduct buildup may result in their release, causing red and turbid water problems.

Like the use of phosphate inhibitors, silicates can combine with other constituents in the delivered water besides the materials targeted for protection. Therefore, sufficient dosages must be applied to compensate for the consumption of silicate by other metals or cations. Specifically, calcium and magnesium will readily react with silica over a large pH range. Also, silicates are frequently used by small water systems supplied by groundwater for iron control. Silicates can sequester



soluble iron and manganese present in the source water to reduce red and black water events. Attention to the water quality conditions prior to their application is necessary depending on the intended use and performance of the silicate. The additional sodium contributed by sodium silicate formulations should also be considered by PWSs.

### ***3.3 Evaluating Alternative Corrosion Control Approaches***

The label "corrosion control" has historically been applied to a variety of water treatment techniques which are frequently used to meet differing water quality objectives. Until quite recently, corrosion control practices by PWSs were typically designed to improve aesthetics, protect marginal hydraulic capacity, and/or reduce long-term pipeline maintenance. Although these objectives remain worthwhile, they have little to do with LCR compliance, which essentially has *redefined* corrosion control primarily on the basis of public health impacts. The principal objective of the LCR is to minimize the concentration of lead and copper in drinking water without compromising other health-related water quality goals. This has created some confusion within certain water supply utilities where long-standing corrosion control procedures are now being found "ineffective" with respect to the new objectives.

A wide variety of proprietary chemicals have evolved to control pipeline and valve deterioration, eliminate "dirty water" complaints, reduce laundry staining, etc. Some of these "corrosion inhibitor" chemi-

cals can also help reduce lead and copper levels in drinking water, although many will not and some could even increase lead concentrations. Comparisons of corrosion inhibitors is often controversial because of the proprietary nature of the specific chemical formulations and varying water chemistries. This issue is further complicated by a lack of understanding by many users about the differences between chemical products (e.g., ortho and polyphosphates) and their relationship to the formation of metallic precipitates and protective films in potable water systems.

Beyond compliance with the LCR and other drinking water standards, additional benefits and detractions from the installation of corrosion control treatment may also be considered when alternative treatment approaches are reviewed and assessed. Some examples of the secondary issues which may be important to PWSs include:

- Improve the aesthetic quality of the potable supply (reducing customer complaints).
- Provide cost savings on the operation and maintenance of the distribution system.
- Extend the sludge disposal options available to wastewater treatment plants (POTWs) by reducing the overall metal content of the domestic wastewater.
- Extend the usable life of customer water systems, especially hot water heaters or industrial applications.
- Minimize any unnecessary public exposure to corrosion byproducts, such as heavy metals or asbestos fibers.
- Reduce or, at least, not foster microbial growth in the distribution system.

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- Disturb existing coatings in distribution system piping.
- Develop compatible treatment approaches for multiple sources of supply to a distribution system.
- Improve or maintain the hydraulic capacity of a distribution system.

PWSs must exercise caution in selecting technology which is consistent with conflicting water quality objectives. While it is not possible to devise a universal approach for selecting the best corrosion control scheme, the information provided below is designed to identify interactions between LCR treatment goals and those associated with other SDWA regulations. The use of chemical treatment to reduce lead and copper in drinking water will be dependent upon many site-specific chemical and physical interrelationships and may require side-by-side demonstration testing to assess performance.

Those small and medium-size PWSs exceeding an AL during initial monitoring must submit recommendations for optimal treatment to the State. Large PWSs required to perform corrosion control studies will also have to submit either recommendations for optimal treatment or the alternative treatment approaches to be evaluated further as a result of the desk-top evaluation. To assist in the development of these recommendations, the following sections provide a step-by-step procedure to be used to evaluate alternative treatment approaches and a basis for the selection of optimal treatment.

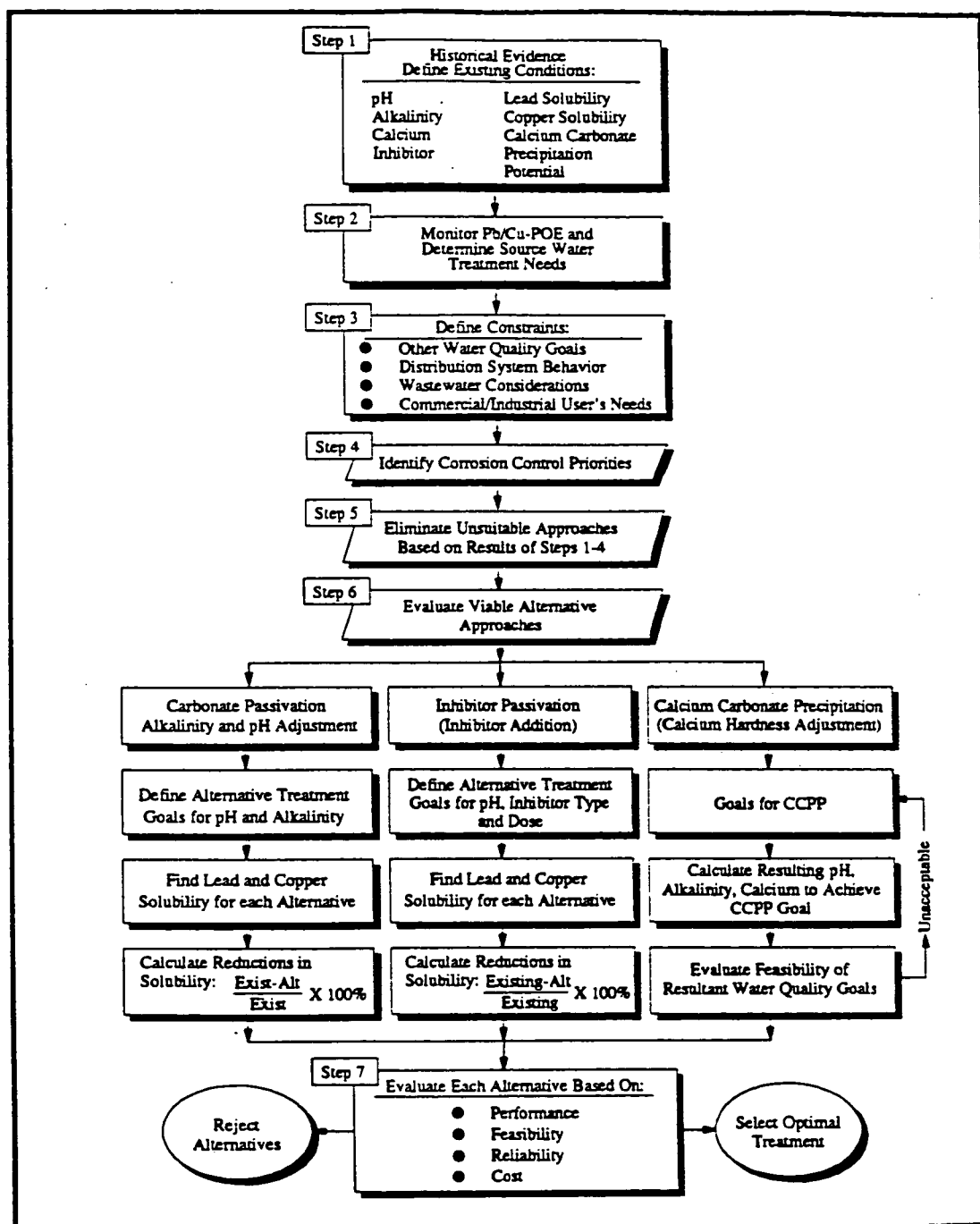
### 3.3.1 Steps to Corrosion Control Assessments.

In order to provide a treatment recommendation to the State, those small and medium-size PWSs required to install optimal corrosion control treatment should assess the three general approaches discussed above by a *desk-top evaluation*. The logic diagram shown in Figure 3-6 presents the process involved in performing desk-top evaluations for selecting optimal treatment. This procedure allows systems to eliminate initially any treatment approaches which are infeasible and to then determine the water quality conditions defining optimal corrosion control treatment for the feasible alternatives. Among the resultant alternatives, optimal treatment is to be selected on the basis of the following criteria:

- the results of lead and copper tap sampling;
- corrosion control **performance** based on either the reductions in metal solubility or the likelihood of forming a protective scale;
- the **feasibility** of implementing the treatment alternative on the basis of the constraints identified;
- the **reliability** of the alternative in terms of operational consistency and continuous corrosion control protection; and,
- the estimated **costs** associated with implementing the alternative treatments.

The first step is to describe the existing conditions of the PWS in terms of its water quality parameters. As part of this first

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**Figure 3-6. Logic Diagram for Evaluating Alternative Corrosion Control Approaches**

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step, PWSs can estimate the theoretical lead and copper solubility as well as the potential for calcium carbonate precipitation based on the existing water quality conditions. Changes in water quality conditions for alternative treatments can be compared to the existing conditions to determine their relative performance and potential to reduce corrosion.

Each PWS operates under certain constraints, such as specific water quality goals, existing coatings in distribution system piping, multiple sources of supply of varying water quality, and wastewater permit limits on metals or nutrient levels which may be improved or compromised by corrosion control treatment. Any constraint which could impact the feasibility of implementing an alternative treatment should be identified and documented. This information will be important to the selection of those treatment options which are viable alternatives for the PWS to consider further.

Based on the water chemistry of the supply and site-specific constraints, the PWS may eliminate corrosion control treatment approaches which would be infeasible to implement successfully. The remaining options, deemed to be feasible, should be evaluated on the basis of each PWS's corrosion control treatment priorities to properly judge the performance of the alternative approaches. For example, a system which experiences lead levels in first-draw tap samples greater than the AL for lead should set lead control as its primary goal. A second system which finds low lead levels, but has elevated copper levels in first-draw tap samples should set copper as the primary objective of

corrosion control treatment. However, in the latter case, optimal treatment should not worsen lead corrosion behavior and therefore, the control of lead may be considered as a constraint acting on the decision-making process for selection of optimal treatment.

Each of the three corrosion control treatment approaches that are viable options should be evaluated to determine the water quality characteristics which describes optimal treatment within each option. For the passivation methods, alternative treatments are evaluated by comparing their relative reduction in the solubility of each targeted metal (lead and/or copper). The calcium carbonate precipitation method is evaluated by the ability of alternative treatments to produce sufficient potential for scale-forming conditions to exist in the distribution system. The "rule of thumb" guidelines presented in Appendix A may be used to rank the alternatives evaluated within this treatment approach.

The final selection of optimal treatment will rest on the four factors discussed above: performance, feasibility, reliability, and costs. Direct comparison of corrosion control performance for alternative treatment approaches may be not possible. Professional judgement and related experiences will be necessary to provide a basis for ranking alternatives on the basis of performance.

The following sections provide more detailed descriptions of the various steps involved in performing a desk-top evaluation of alternative treatments and the development of final recommendations for optimal treatment.

### 3.3.2 Documenting Historical Evidence.

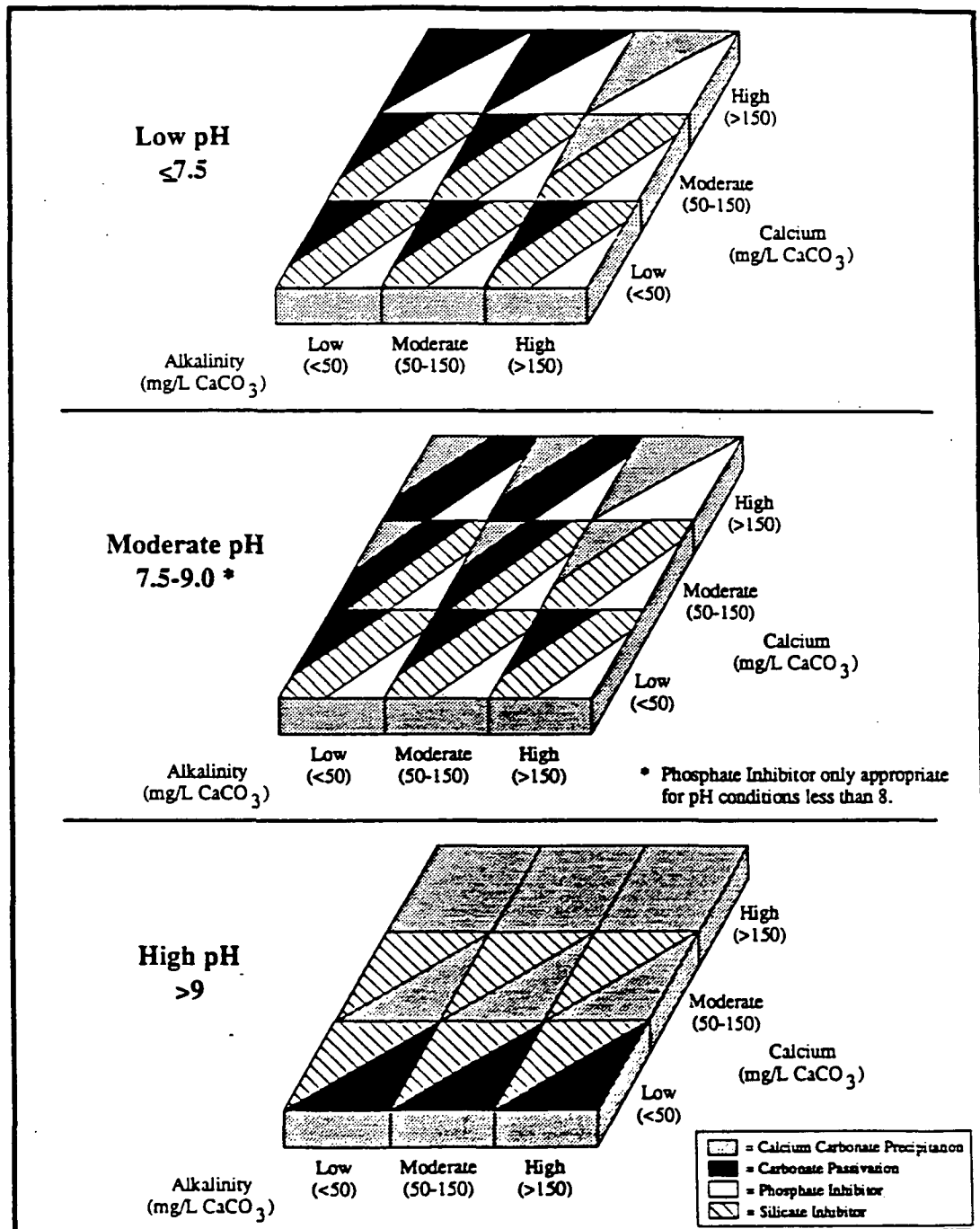
The first step of the desk-top evaluation is to identify and document any existing information pertinent to the evaluation of corrosion control for the system. Four categories of data should be compiled: (a) water quality data; (b) evidence of corrosion activity; (c) available results of corrosion studies performed by other PWSs as reported in the literature that meet LCR conditions, i.e. similar water chemistry, distribution system, etc.; and (d) results from prior corrosion studies or testing performed by the PWS. The most pertinent information is the results of any prior corrosion control testing performed by the system. Beyond the direct testing results, a comprehensive review of the other sources of information should be conducted by the PWS.

**3.3.2.1 Water quality data.** Current and historical water quality data should be compiled and analyzed. The key parameters of interest include pH, alkalinity, hardness, total dissolved solids or conductivity, temperature, dissolved oxygen, and metals (eg., aluminum, manganese, iron, lead, and copper). These basic water quality parameters only represent those most commonly required. Site-specific requirements should be considered in the selection of water quality parameters for review. The data collected should pertain to raw and finished water conditions, as well as the water quality within the distribution system, if available. Additionally, the results of the initial monitoring program should be considered when available.

Understanding the treatment processes at a PWS facility and their respective impacts on water chemistry is an important aspect of interpreting the water quality data and evaluating the appropriateness of alternative corrosion control treatment techniques. Figure 3-7 illustrates the relationship between water quality and alternative corrosion control treatment approaches. Three major regions are shown on the basis of pH (low, moderate, and high) with alternative treatment approaches which may be viable on the basis of water quality shown for each block by its respective alkalinity and calcium levels (low, moderate, or high). To demonstrate the use of Figure 3-7, consider a PWS with a pH 7.8, alkalinity of 40 mg  $\text{CaCO}_3/\text{L}$ , and calcium content of 60 mg  $\text{CaCO}_3/\text{L}$ . The moderate pH (7.5-9.0) chart is used with treatment alternatives corresponding to the block for low alkalinity (<50 mg  $\text{CaCO}_3/\text{L}$ ), and moderate calcium (50-100 mg  $\text{CaCO}_3/\text{L}$ ). On the basis of water quality alone, this PWS should consider all four treatment alternatives as viable.

In many cases, site-specific water quality conditions will reduce the feasibility of an alternative treatment approach. For example, it would be reasonable to eliminate the calcium carbonate precipitation option as a viable treatment approach for those PWSs exhibiting low pH, alkalinity, and hardness in the treated water due to the excessive chemical modifications which would be required to achieve sufficient calcium carbonate precipitation in the distribution system.

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**Figure 3-7. Suggested Corrosion Control Approaches Based on Water Quality Characteristics**

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Conversely, a PWS exhibiting high pH conditions with moderate to high alkalinity and calcium contents might concentrate their efforts on calcium carbonate precipitation for the following reasons:

- While high pH conditions may be optimal for lead control, these water quality conditions are very aggressive towards iron corrosion and would most likely cause severe degradation in distribution system water quality should calcium carbonate precipitation not be pursued; and
- High dosages of corrosion inhibitors may be necessary to maintain an effective residual throughout the distribution system due to the presence of calcium. Also, some inhibitors can cause existing corrosion byproducts to be released in the distribution system causing water quality degradation.

Figure 3-7 is intended to provide general guidelines on water quality conditions versus alternative treatment approaches; it is not intended to serve as the sole basis for selection or elimination of the available alternatives. Further, caution must be raised any time a corrosion control approach requires a severe modification in the existing water quality entering the distribution system. Disruptions and upset of existing corrosion byproducts will impact the overall effectiveness of any corrosion control treatment approach.

**3.3.2.2 Corrosion activity.** Existing records indicative of corrosion activity within the distribution and home plumbing systems should be identified and analyzed to inform the PWS of the nature and extent of corrosion activity anticipated

within the service area. Evidence of corrosion activity may be obtained by: (1) reviewing customer complaint records for dirty water or metallic taste and odor events, (2) performing an informal survey of area plumbers regarding the frequency and nature of plumbing repairs (especially, for example, hot water heater replacements), (3) reviewing records citing the inspection of distribution system mains and service line when being replaced or repaired, (4) installing and evaluating corrosion coupons placed within the distribution system, and (5) water quality monitoring for metals or other corrosion byproducts within the distribution system or home plumbing environments.

While the information listed above may, in some instances, be incidental in nature - i.e., causative relationships may not be easily developed between the observed effects of corrosion activity and the water quality within the distribution system, PWSs may gain a more complete sense of the corrosion concerns facing their system.

**Example:** After reviewing several years of data, a PWS observed that complaints from customers about red water was the predominant source of dissatisfaction with the water supply and that the number of complaints was increasing in recent years. The utility manager interviewed City plumbing inspectors, local plumbers, and the PWS's maintenance department about corrosion activity to learn more about the potential problems. As a result of these inquiries, it was discovered that (a) the average life of household water heaters in the PWS's service area is one half of that expected normally; (b) copper plumbing in

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residences often experienced pitting corrosion resulting in pin-hole failures of piping; and (c) the highest repair and replacement rate for distribution system mains and service lines was in the older parts of the service area where unlined cast iron mains and galvanized service lines were still in-place. Based on these findings, the utility manager initiated a monitoring program to determine the presence of corrosion byproducts and water quality conditions in the distribution system and at employees homes. The incidental information indicated that copper and iron corrosion were concerns for the PWS, both in terms of material failure and water quality. The monitoring program confirmed these concerns, finding pH and alkalinity shifts within the cast iron distribution system and elevated copper levels in home tap samples. While the information gathered by the utility manager did not determine the specific cause of the distribution and home plumbing system corrosion, it did further the PWS's understanding of the potential corrosion problems in its service area. It also served as a basis for designing a water quality monitoring program to the corrosion activity experienced in the distribution and home plumbing systems after installation of treatment.

Several factors should be considered in evaluating the usefulness of this information; namely: (1) the frequency of data collection; (2) the number of coupons, if used, and their locations within the distribution system; (3) the analytical methods and their respective detection limits; (4) the consistency of the data temporally and spatially; and (5) the reliability of the incidence reports.

Included in this pool of information should be the results of the initial monitoring program required by the Lead and Copper Rule, if available.

This information may be used to prioritize the corrosion control program elements for the PWS in terms of the key materials for protection and assess the general effectiveness of the existing treatment approach.

### 3.3.2.3 Review of the literature.

A search and review of the available literature should be performed to ascertain: (1) the findings of similar systems when performing corrosion control testing; and (2) the theoretical basis for alternative corrosion control approaches to be considered by the PWS - thereby, eliminating those approaches which appear to be infeasible.

Several corrosion control studies have been performed and the results published by several water suppliers in the United States. Each study has site-specific goals and objectives relevant to the testing protocols as well as water treatment and quality conditions. However, the experiences of these systems provide a useful resource to other PWSs investigating corrosion control in terms of: (1) study design and execution; (2) data handling and interpretation; and (3) recommended treatment given the goals and constraints acting on the system. A summary of the available literature on corrosion control studies is provided in Appendix B. Note that great care must be taken in evaluating studies reported in the literature so that test protocol, water chemistry, treatment processes, and so forth are matched as closely as possible.



**3.3.2.4 Prior experience and studies.** Corrosion control treatment is not a new concern for water suppliers, and many have performed studies in the past to assist in the design and implementation of corrosion control treatment. These past experiences and studies should be revisited by PWSs to incorporate their findings and results in the present evaluation of corrosion control for lead and copper. Small systems could use the optimum corrosion control treatment processes which were recommended to the State by the larger PWSs. In some cases, the prior testing targeted lead and copper control, and these findings would be directly applicable to the corrosion control study objectives for the Lead and Copper Rule. Additional testing may not be necessary, therefore, to formulate recommendations for optimal corrosion control treatment (if not already considered to be in place).

**Example:** The Town of Redfield, a small PWS operating a groundwater well, found lead levels above the action level during initial monitoring. In order to prepare recommendations for optimal treatment, the PWS operator began collecting information regarding the condition of distribution system materials and the experiences of nearby towns and communities. From previous pipe replacement activities, the PWS operator had noticed a thin, buff-colored deposit on the walls of distribution system piping. The groundwater source is well buffered with an average pH 7.4, alkalinity of 160 mg  $\text{CaCO}_3/\text{L}$ , and calcium hardness of 110 mg  $\text{CaCO}_3/\text{L}$ . The CCPP calculated for the system is -2.4 mg  $\text{CaCO}_3/\text{L}$ .

Redfield needed to determine whether they were successfully coating the pipes

of the distribution and home plumbing systems with calcium carbonate deposits. Plumbing materials from service lines, distribution mains, and three homes in the service area were extracting during repair in order to chemically analyze the constituents present in the scale. This analysis confirms that the scale was predominantly calcium carbonate. However, observation of the same showed that it was not uniformly coating the pipe materials, especially the home plumbing piping.

The PWS considered the alternative treatment approaches for corrosion control and eliminated pH/alkalinity adjustment (*carbonate passivation*) due to the excessive alkalinity and calcium levels per Figure 3-7 presented in the *LCR Guidance Manual*. The remaining alternatives were calcium hardness adjustment and corrosion inhibitors.

A nearby township having wells located in the same aquifer as Redfield had previously installed orthophosphate inhibitor feed facilities for corrosion control. After orthophosphate addition, the treated water had a final pH of 7.35 and  $\text{PO}_4$  concentration of 5 mg  $\text{PO}_4/\text{L}$  to account for the phosphate demand exerted by the calcium present in the well water and to produce an effective residual throughout the distribution system. Their experience was not altogether positive, having a significant number of turbid and dirty water complaints occurring after the addition of the orthophosphate. Additionally, within three months of beginning the phosphate treatment, it appeared that the hydraulic capacity of the distribution mains in the vicinity of the well heads was being significantly reduced. They gave up

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the use of the corrosion inhibitor in order to restore the aesthetic quality of the delivered water supply.

After learning of these experiences, the Town of Redfield decided to eliminate the use of orthophosphate from their alternative corrosion control treatment approaches. Redfield focused their evaluation on the calcium carbonate precipitation technique for the following reasons:

- The CCPP condition for the finished water supply could be readily improved to produce a more reliable calcium carbonate deposit on the pipe walls. This deposit can further be controlled once treatment is in-place by dissolution and precipitation conditions in the treated water to ensure that the hydraulic capacity of the system is not compromised.
- Little documentation exists to confirm the corrosion control performance of silicate inhibitors with respect to lead and copper corrosion control for supplies with high calcium contents.
- Difficulties may arise in controlling silicate-based deposits to maintain the hydraulic capacity of the distribution system since they are not able to be redissolved.

Based on a CCPP goal of 8.5 mg  $\text{CaCO}_3/\text{L}$ , Redfield determined that a pH of 7.9 was needed for its finished well water supply.

### ***3.3.3 Identifying Constraints.***

The Rule provides two conditions by which constraints may be considered in limiting the availability of alternative

corrosion control treatments. Namely, options which have been shown either: (1) to adversely impact other water treatment processes and cause a violation of a National Primary Drinking Water Regulation; or (2) to otherwise be ineffective for the PWS.

EPA recommends that all constraints acting on PWSs be identified and considered in the selection of treatment approaches either for additional testing or as the recommended treatment process. Worksheets are provided in Table 3-3 for each of the three treatment alternatives (pH/alkalinity adjustment, calcium adjustment, and corrosion inhibitors) to assist PWSs in evaluating the constraints acting on their systems. Constraints have been extracted from an overview of corrosion control literature (Swayze, 1983; AWWARF, 1990c; Benjamin, 1990; AWWARF/DVGW, 1985; AWWA, 1986; AWWA, 1989).

PWSs should evaluate the impact of alternative corrosion control treatment options on regulatory compliance with existing federal and state drinking water standards in addition to those regulations anticipated to be finalized within the time frame for corrosion control installation by small and medium PWSs. Table 3-4 presents the schedule for regulatory actions during the next decade in conjunction with the compliance timeline for medium-size and small system implementation steps for the Lead and Copper Rule. The key regulatory actions which should be fully evaluated by small and medium PWSs for selecting optimal corrosion control treatment are discussed at more length below.

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**Table 3-3a. Constraints Worksheet for pH/Alkalinity or Calcium Adjustment Treatment Alternatives**

<p><i>Adjusting pH/Alkalinity and/or calcium for corrosion control typically consists of increasing their levels to generate favorable conditions for lead and copper passivation or calcium carbonate precipitation.</i></p>	
<b>A. National Primary Drinking Water Regulations Constraints</b>	
<b>Rule</b>	<b>Constraint</b>
Surface Water Treatment Rule	<p>Reduces inactivation effectiveness of free chlorine if pH adjusted before disinfection.*</p> <p>Potential for interference with dissolved ozone measurements.</p> <p>May increase turbidity from post-filtration precipitation of lime, aluminum, iron, or manganese.</p>
Groundwater Disinfection	<p>Reduces inactivation effectiveness of free chlorine if pH adjusted before disinfection.*</p> <p>Potential for interference with dissolved ozone measurements.</p>
Disinfection Byproducts	<p>Higher THM concentrations from chlorination if pH adjusted before disinfection.*</p> <p>Reduced effectiveness of some coagulants for precursor removal if pH adjusted before coagulation.*</p>
Coliform Rule	<p>Potential for higher total plate counts, confluent growth, or presence of total coliforms when chlorination is practiced.</p>
Radionuclides	<p>In-plant adjustments may affect removal of radioactive particles if precipitation techniques are used for coagulation or softening.</p> <p>Removal of radionuclides during softening may be linked to the degree of softening. Modifying softening practices to achieve corrosion control could interfere with removals.</p>

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**Table 3-3a. Constraints Worksheet for pH/Alkalinity or Calcium Adjustment Treatment Alternatives (continued)**

<b>B. Functional Constraints</b>
<p>Increased potential for post-filter precipitation may give undesirable levels of aluminum, iron, or manganese.</p>
<p>Process optimization is essential. Additional controls, chemical feed equipment, and operator attention may be required.</p>
<p>Multiple entry points will require pH/Alkalinity adjustment at each entry location. Differing water qualities from multiple sources will require adjusting chemical doses to match the source.</p>
<p>The use of sodium-based chemicals for alkalinity or pH adjustments should be evaluated with regard to the total sodium levels acceptable in the finished water.</p>
<p>Users with specific water quality needs, such as health care facilities, should be advised of any changes in treatment.</p>
<p>Excessive calcium carbonate precipitation may produce "white water" problems in portions of the distribution system.</p>
<p>It may be difficult to produce an acceptable coating of calcium carbonate on interior piping for large distribution systems. High CCPP levels may eventually lead to reduced hydraulic capacities in transmission lines near the treatment facility while low CCPP values may not provide adequate corrosion protection in the extremities of the distribution system.</p>
<p>* Unless operating restraints dictate otherwise, the optimum location for pH adjustment is after disinfection and near the entrance to the distribution system. If quicklime is used to adjust pH, for example, it needs to be added prior to filtration so inert material does not accumulate in the clearwell or enter the distribution system.</p>

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**Table 3-3b. Constraints Worksheet for  
Inhibitor Treatment Alternatives**

<i>Corrosion inhibitors can cause passivation of lead and copper by the interaction of the inhibitor and metal components of the piping system.</i>	
<b>A. National Primary Drinking Water Regulations Constraints</b>	
<u>Rule</u>	<u>Constraint</u>
Surface Water Treatment Rule	The application of phosphate-based inhibitors to systems with existing corrosion byproducts can result in the depletion of disinfectant residuals within the distribution system. Additionally, under certain conditions phosphate-based inhibitors may stimulate biofilms in the distribution system.
Groundwater Disinfection	Same as above.
Disinfection Byproducts	No apparent effects.
Coliform Rule	If corrosion byproducts are released after the application of inhibitors, coliforms may be detected more frequently and confluent growth is more likely.
Radionuclides	No apparent effects.
<b>B. Functional Constraints</b>	
<p>Potential post-filtration precipitation of aluminum.</p> <p>Consumer complaints regarding red water, dirty water, color, and sediment may result from the action of the inhibitor on existing corrosion byproducts within the distribution system.</p> <p>Multiple entry points will require multiple chemical feed systems.</p> <p>The use of sodium-based inhibitors should be evaluated with regard to the total sodium levels acceptable in the finished water.</p> <p>The use of zinc orthophosphate may present problems for wastewater facilities with zinc or phosphorus limits in their NPDES permits.</p> <p>Users with specific water quality needs, such as health care facilities, should be advised of any treatment changes.</p>	

**NOTE:** If pH adjustment is necessary to produce an effective pH range for the inhibitor, then the constraints in Table 3-3a would also need to be evaluated.

**Table 3-4. Schedule of Drinking Water Regulatory Activity: 1990-2000**

Regulatory Action	Proposal Date	Final Date	Effective Date
Phase I VOCs	11/85	07/87	01/89
Phase II SOCs & IOCs	05/89	01/91 & 07/91	07/92 & 01/93
Phase V SOCs & IOCs	07/90	07/92	01/94
Arsenic	11/92	01/95	07/96
Surface Water Treatment Rule	11/87	06/89	01/91
Total Coliform Rule	11/87	06/89	01/91
Radionuclides Rule	07/91	04/93	10/94
Groundwater Disinfection Rule	06/93	06/95	01/97
Disinfectants/Disinfection By-Products	06/93	06/95	01/97
Lead and Copper Rule	08/88	06/91	07/91 & 12/92

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- **Surface and Groundwater Treatment Rules (SWTR/GWTR)** where PWSs will be required to meet disinfection performance criteria. Disinfection efficiency is pH dependent for free chlorine where less effective disinfection results under higher pH conditions.
- **Total Coliform Rule (TCR)** which requires all PWSs to meet minimum occurrence standards for the presence of total and fecal coliforms in distribution system samples. Some PWSs have noted increases in microbiological growth within the distribution system with the installation of corrosion control treatment. However, in most cases, no adverse impact or reductions in heterotrophic plate count bacteria have been found after implementing corrosion control treatment.
- **Disinfectants/Disinfection Byproducts Rule (D/DBPR)**, currently under development, will be finalized within the same time frame as PWSs are installing corrosion control treatment as a result of the Lead and Copper Rule. Adjusting pH conditions can affect the level of certain DBPs, most notably, total trihalomethanes (TTHMs) and total haloacetic acids (THAAs). These two contaminant groups are likely to be included in the future DBPR, and they exhibit opposite relationships to pH adjustment; TTHM formation increases with increasing pH, while THAA formation increases with decreasing pH. An additional consideration is the point of pH adjustment within treatment plants since lower pH conditions favor increased removal of DBP precursors during coagulation by alum. Compliance with the DBPR could be compromised by increasing the pH of coagulation as part of the corrosion control treatment approach as it may

reduce the efficiency of conventional treatment in removing precursor material.

Additional constraints should be considered by PWSs beyond those required by the Rule. As presented in Table 3-3b, a selected number of such limiting conditions for alternative corrosion control approaches include:

- Compatibility of a treatment approach with multiple sources of supply.
- Compatibility of a treatment approach for consecutive systems.
- Reliability features for the particular treatment approach, including: (1) process control; (2) operational redundancy requirements; and (3) chemical supply integrity and availability.
- Adverse impacts on the service community, including: (1) commercial users' water quality criteria; (2) health-care facility water quality criteria; and (3) wastewater operations - permit requirements for discharges and solids handling programs.

The particular conditions which define the constraints for each system will be site-specific, and should be thoroughly investigated as part of the desk-top evaluation aspect of the corrosion study. Small and medium systems exceeding the ALs but not required to perform testing should consider each of these items when selecting the optimal treatment for recommendation to the State. For those large PWSs required to perform only a desk-top evaluation, rigorous documentation of any constraints must be presented to support the recommended treatment approach for the system. For any PWS performing corrosion testing, the availability of information regarding system constraints will assist in limiting the optional treatment approaches which must be evaluated through the testing program.

**Example:** After exceeding the lead AL during initial monitoring, the City of Dannyport

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began investigating alternative corrosion control treatment measures to provide the State with recommendations for optimal treatment. The City determined through its desk-top evaluation that raising the pH of the treated water was a viable treatment approach. Two alternative pH levels were identified for further consideration. As a medium-size surface water facility, concerns were raised regarding compliance with the SWTR and the ultimate feasibility of implementing pH adjustment.

The existing treatment provided by Dannyport is conventional coagulation/ flocculation with rapid sand filtration. Under the SWTR, at least 0.5-logs of inactivation of *Giardia* and 2.0-logs of virus inactivation were required.

The SWTR applied CT values - the product of the disinfectant *concentration* at the end of a disinfection segment and the effective contact *time* available within the disinfection segment, to determine the inactivation achieved during treatment. The *SWTR Guidance Manual* (USEPA, 1989) defined the  $CT_{req}$  as the CT value **required** to achieve the desired level of inactivation. The  $CT_{act}$  was defined as the CT value **actually** achieved through treatment for each disinfection segment within a water treatment facility. Compliance with the disinfection requirements is achieved when the sum of the  $CT_{act}:CT_{req}$  ratios for all disinfection segments in a facility is greater than or equal to 1.0.

For the *Giardia* requirements, the existing plant's performance was determined to be adequate to meet the CT required with the sum of the  $CT_{act}:CT_{req}$  ratios equal to 1.2. Virus inactivation performance was satisfactory and would not be affected by pH changes. However, *Giardia* inactivation performance is a function of pH. At the higher pH levels under consideration for corrosion control, the sum of the  $CT_{act}:CT_{req}$  ratios would be 0.90 and 0.83,

respectively. Neither case would provide adequate disinfection performance.

An additional concern is continued compliance with the Total Trihalomethane (TTHM) standard. Currently, an average of 60  $\mu\text{g/L}$  TTHM is found in the distribution system with seasonal peaks of nearly 100  $\mu\text{g/L}$  TTHM. As such, increasing the pH of the finished water supply could only increase the probability of Dannyport exceeding the future TTHM standard, expected to be finalized concurrently with the City's initiation of corrosion control treatment.

Given the above regulatory concerns, the City of Dannyport determined that pH adjustment would not be a feasible option.

### 3.3.4 Evaluating Source Water Contributions.

When a small or medium PWS exceeds an AL during initial monitoring, lead and copper samples must be collected and analyzed at each point of entry (POE) to the distribution system within six months of exceeding the AL. It is recommended that this monitoring be completed as soon as possible after the AL is exceeded in order to provide information regarding source water lead and copper contributions to the desk-top evaluation effort. The recommendations for treatment which must be supplied to the States within six months of exceeding the ALs must contain source water treatment recommendations in addition to corrosion control treatment recommendations. Therefore, performing lead and copper POE monitoring (Pb/Cu-POE) is critical to the completion of desk-top evaluations.

Table 3-5 presents EPA's guidelines for source water treatment requirements on the basis of lead and copper POE monitoring results. If the source water is contributing more than the AL for either lead or copper, then source water



**Table 3-5. Source Water Treatment Guidelines for Systems Exceeding an AL**

**Note:** States have the discretion to set their own guidelines for Source Water Treatment.

Source Water Treatment Guidelines	Point of Entry Monitoring Results	
	Lead, mg/L	Copper, mg/L
Not Necessary	$\leq 0.005$	$\leq 0.2$
Optional	0.005 — 0.010*	0.2 — 0.8
Recommended	0.010 — 0.015	0.8 — 1.3**
Required	$> 0.015$	$> 1.3$

\* Source water treatment is recommended if the corrosion treatment is at or near optimal and the lead AL is still exceeded.

\*\* If the copper AL is exceeded, source water treatment may be required when corrosion control treatment is unlikely to reduce copper levels below the AL.

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treatment is required. In those cases where a significant amount of lead or copper is present, then treatment is recommended in order to reduce the overall lead or copper exposure and to assist PWSs in meeting the ALs. Table 3-5 also shows that the inclusion of source water treatment is optional when moderate levels of metals are found, and unnecessary when very low levels of either lead or copper are present.

In those cases where systems find elevated levels of lead or copper, the sources of supply should be monitored in the raw water and at various stages within the existing treatment facilities (if providing treatment currently) to determine the source of the metals. This monitoring will also assist in determining whether the existing treatment is already generating any removal of lead and copper.

Several types of treatment may be appropriate for removal of source water lead and copper. EPA specified ion exchange, reverse osmosis, lime softening, and coagulation/filtration as Best Available Treatment (BAT) for removal of lead and copper from source water (USEPA, 1991).

If a PWS is currently providing conventional coagulation/filtration treatment (whether alum or ferric coagulation, iron/manganese removal, or lime softening), then modifying these existing processes may produce the desired removals for lead and/or copper. If treatment is not available, then package treatment units for any of the above technologies may be installed at individual wellheads (especially when the elevated metals are contributed by a small number individual wells) or at a centralized treatment location. In the case of elevated copper, elimination of copper sulfate treatment for those surface water systems employing it as an herbicide or algicide may reduce the background levels of copper without imposing treatment modifications.

States must respond to the recommendations for source water treatment within six months of receiving the submittals from PWSs. If required, PWSs have 24 months to install source water treatment once approved by the State. Source water treatment would be installed, then, six months in advance of corrosion control treatment for medium PWSs and 12 months in advance of corrosion control treatment for small PWSs. Follow-up monitoring would not be required until after all treatment is in place, i.e., after corrosion control treatment has been installed.

### ***3.3.5 Preparing Recommendations for Optimal Treatment.***

Small and medium-size PWSs must submit treatment recommendations to the State within six months of exceeding an AL during initial monitoring. To assist in preparing the recommendations, a checklist (Table 3-6) has been developed summarizing the steps of a desk-top evaluation and key findings. More detailed data and discussion regarding the findings of a desk-top evaluation can be provided in the short form, denoted as Form 141-C, at the end of this chapter. Thus, the checklist (Table 3-6) provides the State with a "map" of the evaluation process and considerations involved in the desk-top procedures employed by a PWS, while Form 141-C presents the State with the findings from the desk-top evaluation. Small and medium PWSs may choose to submit the completed checklist and Form 141-C to the State for purposes of recommending optimal treatment, provided that sufficient documentation is available should the State require additional information during the recommendation review period.

### 3.4 Case Studies

The following case studies illustrate the assessment of source water and corrosion control treatment for PWSs through a desk-top evaluation. Special conditions and considerations have also been shown to assist PWSs and States in addressing the site-specific nature of corrosion control treatment decisions.

#### 3.4.1 Softening Groundwater Supply (Single Source).

The Kashton County Water District (KCWD), a medium-size system, found excessive lead levels (90%Pb-TAP = 22  $\mu\text{g/L}$ ) but low copper levels ((90% Cu-TAP = 0.6 mg/L) during the initial monitoring period for the LCR. Using the checklist presented in Table 3-6, KCWD initiated a desk-top evaluation to determine optimal treatment per the LCR requirements. The first step taken was to monitor each of the five wells servicing the lime softening plant operated by KCWD. No lead or copper was detected in the source water samples, ruling out the need for source water treatment. The recommended treatment must therefore focus on corrosion control alternatives.

Existing water quality data was reviewed, generating average water quality parameter values, estimates of lead and copper solubility, and calculated values for CCPP. Figure 3-8 presents the treatment scheme and resultant water quality data gathered by KCWD. The water quality parameter monitoring conducted within the distribution system showed no major changes in water quality characteristics once the finished water entered the distribution system. Based on Figure 3-7, all corrosion control treatment alternatives are possible for KCWD except the use of orthophosphate since the finished water pH is above 8.

KCWD has never investigated corrosion control treatment in the past, but has noted occasional red water complaints and some tuberculation of unlined cast iron pipes when replaced. The supervisor of the lime softening plant had spoken with another PWS operator also performing lime softening about their experiences with polyphosphate inhibitors. The other community successfully eliminated red water complaints with the use of polyphosphates, but also experienced elevated lead levels during their initial monitoring period.

An evaluation of the constraints acting on KCWD revealed only one known adverse impact: disinfection byproducts. The current TTHM levels are 75  $\mu\text{g/L}$  on average, and increasing the final pH to 9.0 or above would cause this level to increase even further.

Since phosphate inhibitors were eliminated from further consideration, three treatment alternatives remained: pH/alkalinity adjustment; calcium adjustment; and silicate inhibitor addition. Due to the solubility relationships, little benefit or theoretical reductions in lead or copper could be achieved by altering the pH and/or alkalinity of the existing supply. It would require either a pH greater than 9.0, which is not feasible due to TTHM concerns, or increased alkalinity removal during softening which would be difficult to achieve. Therefore, pH/alkalinity adjustment was eliminated as a feasible option.

To evaluate calcium adjustment, a CCPP of 8.0 mg/L  $\text{CaCO}_3$  was selected as an initial target value since it is higher than the existing condition, but will most likely not plug the pipes nearest the plant. To achieve the CCPP goal, either the pH needs to be increased to 8.8 (keeping the alkalinity and calcium the same) or the alkalinity must be increased to 102 mg/L as  $\text{CaCO}_3$  (keeping the pH and calcium content the same). Either method of achieving the CCPP goal is feasible, and this option remains viable.

## SCREENING OF ALTERNATIVES

**Table 3-6. Checklist for PWS Desk-Top Evaluations**

**I. Historical Evidence Review:**

**Did your utility:**

- a. Determine Initial Water Quality  
     WQP-POE and WQP-DIS  
     Pb/Cu-POE  
     Lead Solubility  
     Copper Solubility  
     CCPP Index Value

**YES                  NO**


- b. Conduct Prior Corrosion Control Investigations

--	--

- c. Assess Corrosion Activity in the Distribution System for:  
     Lead and Copper  
     Iron  
     A/C Pipe  
     Other Materials, please specify \_\_\_\_\_


- d. Review the Literature

--	--

- e. Identify Comparable PWS Experience with Corrosion Control Treatment

--	--

(If YES, what was the overall performance of the alternative treatment approaches)

	Very Good	Good	Poor	Adverse
pH/Alkalinity Adjustment				
Calcium Adjustment				
Corrosion Inhibitors				
Phosphates				
Silicates				

- f. Source Water Treatment Status

Required  
 Recommended  
 Optional  
 Not Necessary


## SCREENING OF ALTERNATIVES

**Table 3-6. Checklist for PWS Desk-Top Evaluations (continued)**

- g. Based on your water quality characteristics, check the suggested treatment approach(es) per Figure 3-7 in Volume II of the Guidance Manual.

pH/Alkalinity Adjustment

☐

Calcium Adjustment

☐

Corrosion Inhibitors

Phosphates

☐

Silicates

☐

### II. Constraint Definitions

Is the constraint identified applicable to your system?  
(Based on Rankings of 3 or 4 on Form 141-C)

YES

NO

Regulatory Constraints:

SOCs/IOCs

SWTR: Turbidity

Total Coliforms

SWTR/GWTR: Disinfection

D/DBPs

LCR

Radionuclides


Functional Constraints:

Taste and Odor

Wastewater Permit

Aesthetics

Operational

Other


### III. Were any treatment approaches eliminated from further consideration in the desk-top evaluation?

YES

NO

pH/Alkalinity Adjustment

Calcium Adjustment

Corrosion Inhibitors:

Phosphates

    Zinc Orthophosphate

    Sodium Orthophosphate

    \_\_\_\_\_ Orthophosphate

    Poly-ortho-phosphates

    Polyphosphates

Silicates


## SCREENING OF ALTERNATIVES

**Table 3-6. Checklist for PWS Desk-Top Evaluations (continued)**

**IV. For each of the feasible treatment alternatives, did your system evaluate the following in the desk-top evaluation?**

Performance  
Feasibility  
Reliability  
Costs

YES	NO

**V. What is the recommended treatment approach?**

Source Water Treatment:  
Method, specify:

YES	NO

---



---

Corrosion Control Treatment:

--	--

pH/Alkalinity Adjustment

Calcium Adjustment

Corrosion Inhibitors:

Phosphates

Specify type:


---



---

Silicates

Specify type:

--	--

---



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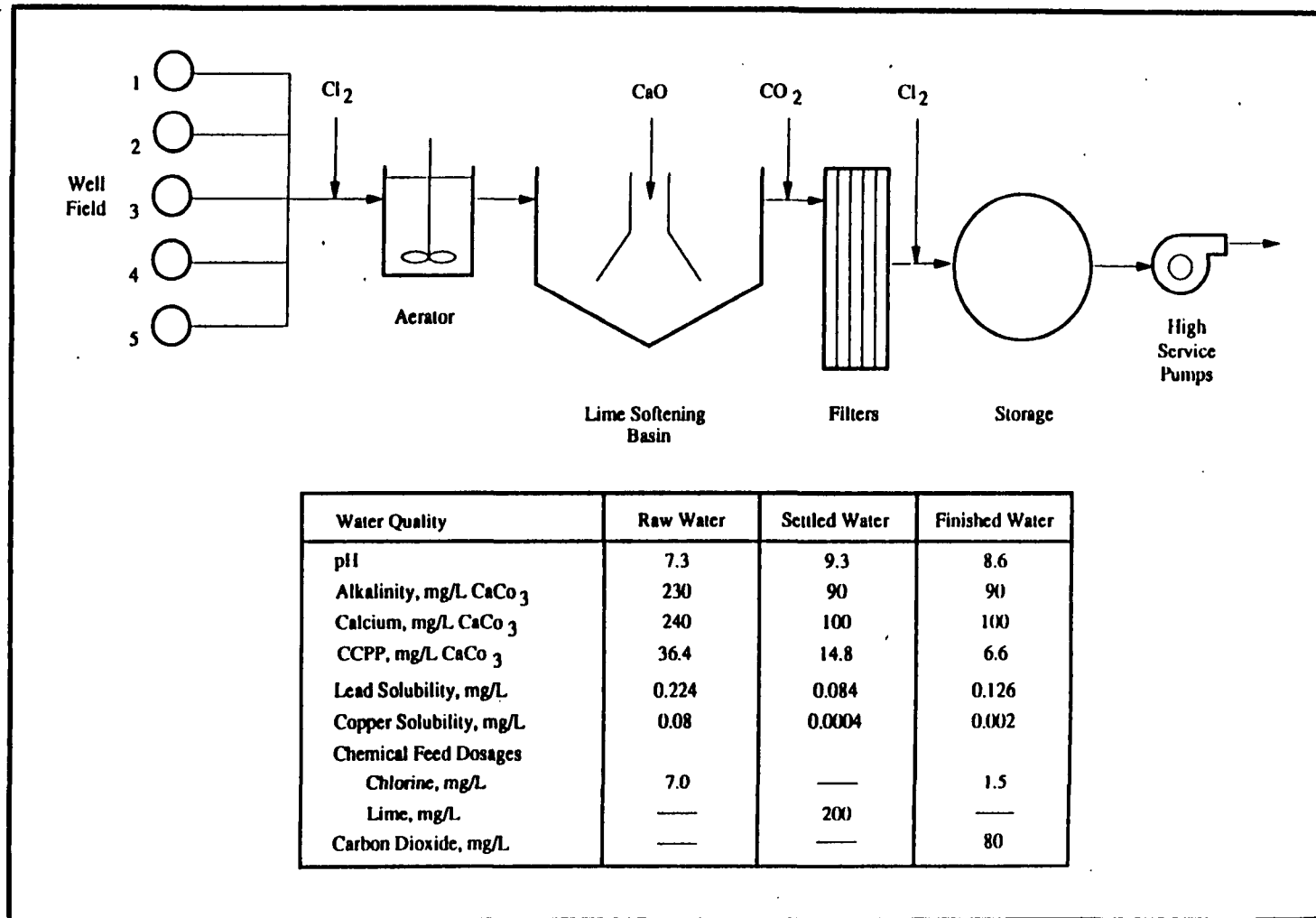


Figure 3-8. Lime Softening PWS: Treatment Schematic and Relevant Data

## SCREENING OF ALTERNATIVES

The use of silicates for corrosion control presented some problems for KCWD in terms of evaluating their usefulness. No other lime softening plant that they knew had any experience with silicates, and yet some promising results had appeared in the literature for different types of supplies. Although they were not required by the Lead and Copper Rule to conduct a treatment study, KCWD decided to do some experimental testing of silicates. Both flow-through and static testing procedures were considered; and after evaluation of the advantages and disadvantages of these methods (see Chapter 4), KCWD decided that the static testing approach was more suitable for their personnel to manage.

The maintenance dosage recommended (10 mg/L  $\text{SiO}_2$ ) was bench-tested with the existing supply and found that it increased the finished water pH to 8.9. However, particles were observed in the containers at the end of the static testing indicating that calcium was probably with the silicate and precipitating. Due to concerns with turbidity problems in the distribution system, the use of silicates were not considered reliable.

Based on the above findings, the recommended treatment was calcium adjustment achieved by increasing either the pH or the alkalinity to meet the CCPP goal of 8.0 mg/L as  $\text{CaCO}_3$ . The KCWD checklist for the desk-top evaluation as presented in Table 3-7 was submitted to the State for approval of the recommended treatment in conjunction with a completed short-form 141-C.

### ***3.4.2 Low Alkalinity, pH, and Hardness Surface Water System.***

The Town of Mulberry provides potable water to its 1,200 residents and operates a small package water treatment plant (WTP) receiving water from the Lolla River - a low alkalinity, pH, and hardness surface water supply. The existing treatment consists of in-line filtration using polymer coagulation and final disinfection with liquid chlorine. Figure 3-9 illustrates the treatment schematic of the WTP and the relevant water quality information for the system.

During the initial monitoring period for lead and copper, excessive lead and copper levels were found at the targeted sites. Source water monitoring revealed high copper concentrations in river samples, such that source water treatment was needed. Lead levels in the Lolla River, however, were below detection and did not require additional source water removal. Corrosion control treatment, however, was still required for Mulberry since the lead levels exceeded the lead AL.

Reviewing the records of the Town, the PWS operator discovered that the water intake at the Lolla River was within a reach of the river where the County applied copper sulfate for algae control. Since the source water monitoring coincided with the period of copper sulfate applications, Mulberry requested that the County use a substitute algicide to reduce the copper levels. Meanwhile, additional source water monitoring was performed by the Town to determine the extent of copper contamination with the river. After three months of no copper sulfate



## SCREENING OF ALTERNATIVES

**Table 3-7. Checklist for the Kashton County Water District  
(KCWD) Desk-Top Evaluations**

**I. Historical Evidence Review:**

**Did your utility:**

- a. Determine Initial Water Quality
- WQP-POE and WQP-DIS
  - Pb/Cu-POE
  - Lead Solubility
  - Copper Solubility
  - CCPP Index Value

YES	NO
✓	
✓	
✓	
✓	
✓	
✓	

- b. Conduct Prior Corrosion Control Investigations

	✓
--	---

- c. Assess Corrosion Activity in the Distribution System for:

- Lead and Copper
- Iron
- A/C Pipe
- Other Materials, please specify

✓	
✓	
	✓
	✓

- d. Review the Literature

✓	
---	--

- e. Identify Comparable PWS Experience with Corrosion  
Control Treatment

✓	
---	--

(If YES, what was the overall performance  
of the alternative treatment approaches)

	Very Good	Good	Poor	Adverse
pH/Alkalinity Adjustment				
Calcium Adjustment				
Corrosion Inhibitors				
Phosphates				✓
Silicates				

- f. Source Water Treatment Status

- Required
- Recommended
- Optional
- Not Necessary

✓

## SCREENING OF ALTERNATIVES

**Table 3-7. Checklist for the Kashton County Water District (KCWD) Desk-Top Evaluations (continued)**

- g. Based on your water quality characteristics, check the suggested treatment approach(es) per Figure 3-7 in Volume II of the Guidance Manual.

pH/Alkalinity Adjustment  
 Calcium Adjustment  
 Corrosion Inhibitors  
 Phosphates  
 Silicates

✓
✓
✓

### II. Constraint Definitions

Is the constraint identified applicable to your system?  
 (Based on Rankings of 3 or 4 on Form 141-C)

#### Regulatory Constraints:

SOCs/OCs  
 SWTR: Turbidity  
 Total Coliforms  
 SWTR/GWTR: Disinfection  
 D/DBPs  
 LCR  
 Radionuclides

YES                      NO

	✓
	✓
	✓
	✓
✓	
	✓
	✓

#### Functional Constraints:

Taste and Odor  
 Wastewater Permit  
 Aesthetics  
 Operational  
 Other

	✓
	✓
	✓
	✓
	✓

### III. Were any treatment approaches eliminated from further consideration in the desk-top evaluation?

pH/Alkalinity Adjustment  
 Calcium Adjustment  
 Corrosion Inhibitors:  
     Phosphates  
         Zinc Orthophosphate  
         Sodium Orthophosphate  
         \_\_\_\_\_ Orthophosphate  
         Poly-ortho-phosphates  
         Polyphosphates  
 Silicates

YES                      NO

	✓
	✓
✓	
✓	
✓	
✓	
✓	
	✓

## SCREENING OF ALTERNATIVES

**Table 3-7. Checklist for the Kashton County Water District (KCWD) Desk-Top Evaluations (continued)**

**IV. For each of the feasible treatment alternatives, did your system evaluate the following in the desk-top evaluation?**

Performance  
Feasibility  
Reliability  
Costs

YES	NO
<input checked="" type="checkbox"/>	<input type="checkbox"/>
<input checked="" type="checkbox"/>	<input type="checkbox"/>
<input checked="" type="checkbox"/>	<input type="checkbox"/>
<input checked="" type="checkbox"/>	<input type="checkbox"/>

**V. What is the recommended treatment approach?**

Source Water Treatment:  
Method, specify:

YES	NO
<input type="checkbox"/>	<input checked="" type="checkbox"/>

Corrosion Control Treatment:

<input checked="" type="checkbox"/>	<input type="checkbox"/>
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pH/Alkalinity Adjustment

Calcium Adjustment

Corrosion Inhibitors:

Phosphates

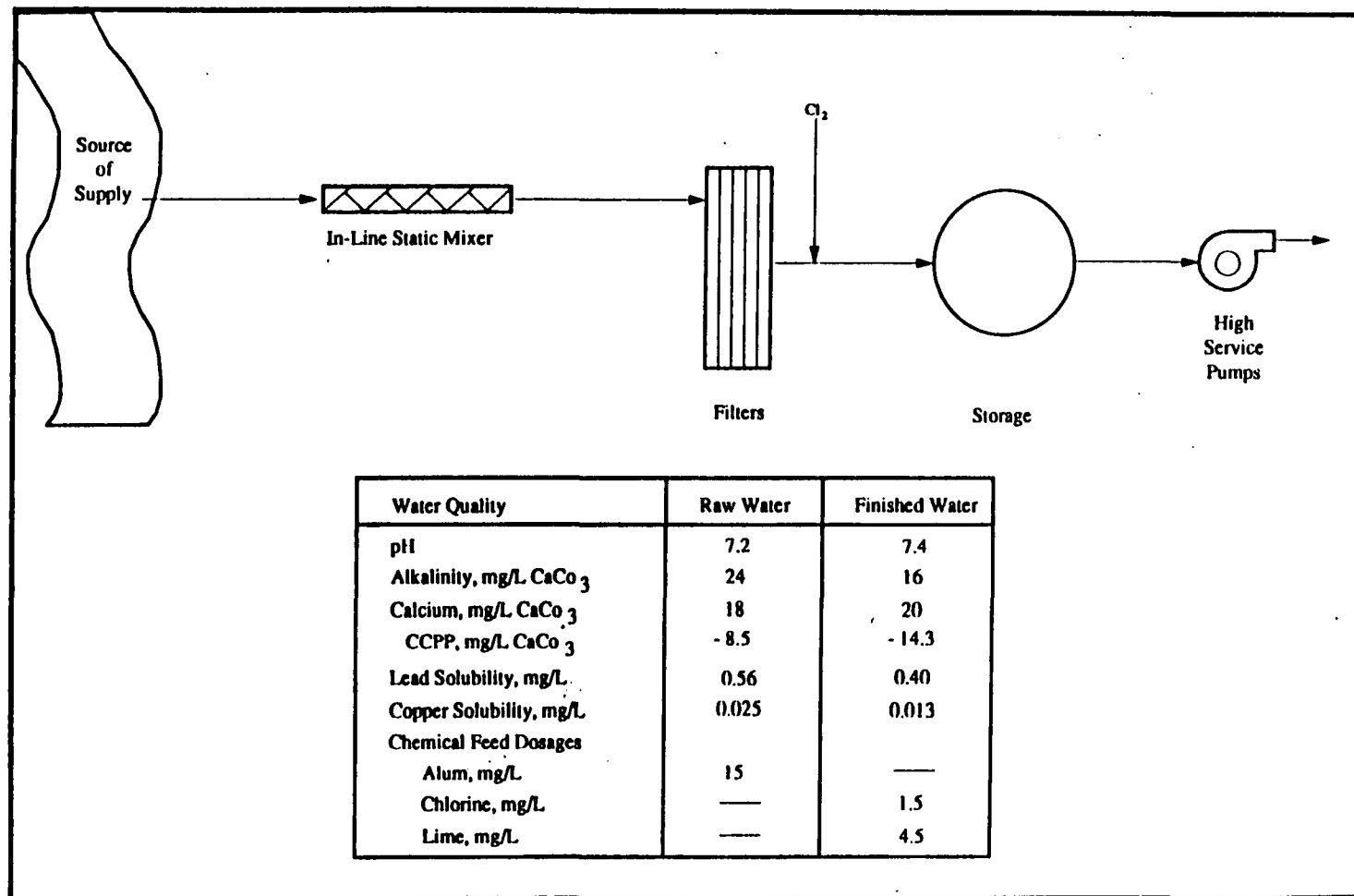
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<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>

Silicates

Specify type:

<input type="checkbox"/>	<input type="checkbox"/>
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**Figure 3-9. Surface Water PWS with Low Alkalinity, pH, and Hardness: Treatment Schematic and Relevant Data**

## SCREENING OF ALTERNATIVES

applications, the source water copper levels were less than 0.02 mg/L copper. The PWS and the State agreed that additional source water treatment would not be necessary as long as the County did not apply copper sulfate in the reaches of the river directly above Mulberry's intake.

Meanwhile, corrosion control treatment investigations resulted in eliminating pH/alkalinity adjustment and calcium adjustment as viable treatment alternatives. Limited storage is available at the Mulberry package plant, and raising the pH even slightly would jeopardize the disinfection performance capability of the plant. Additionally, the low alkalinity, pH, and calcium content of the water indicated that formation of calcium carbonate deposits would require excessive chemical treatment. The use of inhibitors was selected as the approach of choice for the Town.

Phosphate inhibitors were considered preferable to the silicates given their proven performance in the available literature. Since the control of lead was the targeted objective of corrosion control treatment, zinc orthophosphate was recommended as the optimal treatment approach for Mulberry. Aware of the possibility for initial disturbances within the distribution system, Mulberry instituted a flushing program simultaneously with the startup of the phosphate feed. Higher dosages were selected to initiate the system (3.0 mg/L as  $\text{PO}_4$ ) with a maintenance dose of 0.6 mg/L as  $\text{PO}_4$  based on the experiences of two other communities that had worked with Mulberry's chemical supplier.

### ***3.4.3 Multiple Sources of Supply.***

Chinnee County, a medium-size system, is in the process of building a new water

treatment plant which will receive surface water from the Monohaggen Water Project. Currently, the County operates several groundwater wells (See Figure 3-10) which have been experiencing increasing iron and manganese levels over the last several years. The objective of the County is to provide the base-load of the distribution system's water demand through the new WTP and continue to use the well supply during periods of high demand.

During the initial monitoring program, the lead and copper ALs were met by the County. The 90th percentile lead level was 0.012 mg/L and 0.010 mg/L for the first and second monitoring periods, respectively. The County applied to the State for reduced monitoring.

While corrosion control treatment is not required at present, concerns have been raised about the corrosion control performance of the distribution system when the new WTP is brought on line as the main supply source for the County. The groundwater supply is well-buffered and contains a moderate amount of calcium hardness. The CCPP for the wells averages 9.2 mg/L as  $\text{CaCO}_3$ . However, the surface water source is poorly buffered, contains little hardness, and would have a moderate to low pH after treatment. The existing calcium carbonate films may not be maintained within the distribution system once supplied by the surface water.

Many residences in the county were constructed in the early 1900s and still have lead service lines in place. The County is concerned that future exceedances of the lead AL could invoke LSL replacement requirements, an expense that the County does not want to undertake. Additionally, the design of the surface water plant included provisions for additional chemical feed systems if needed

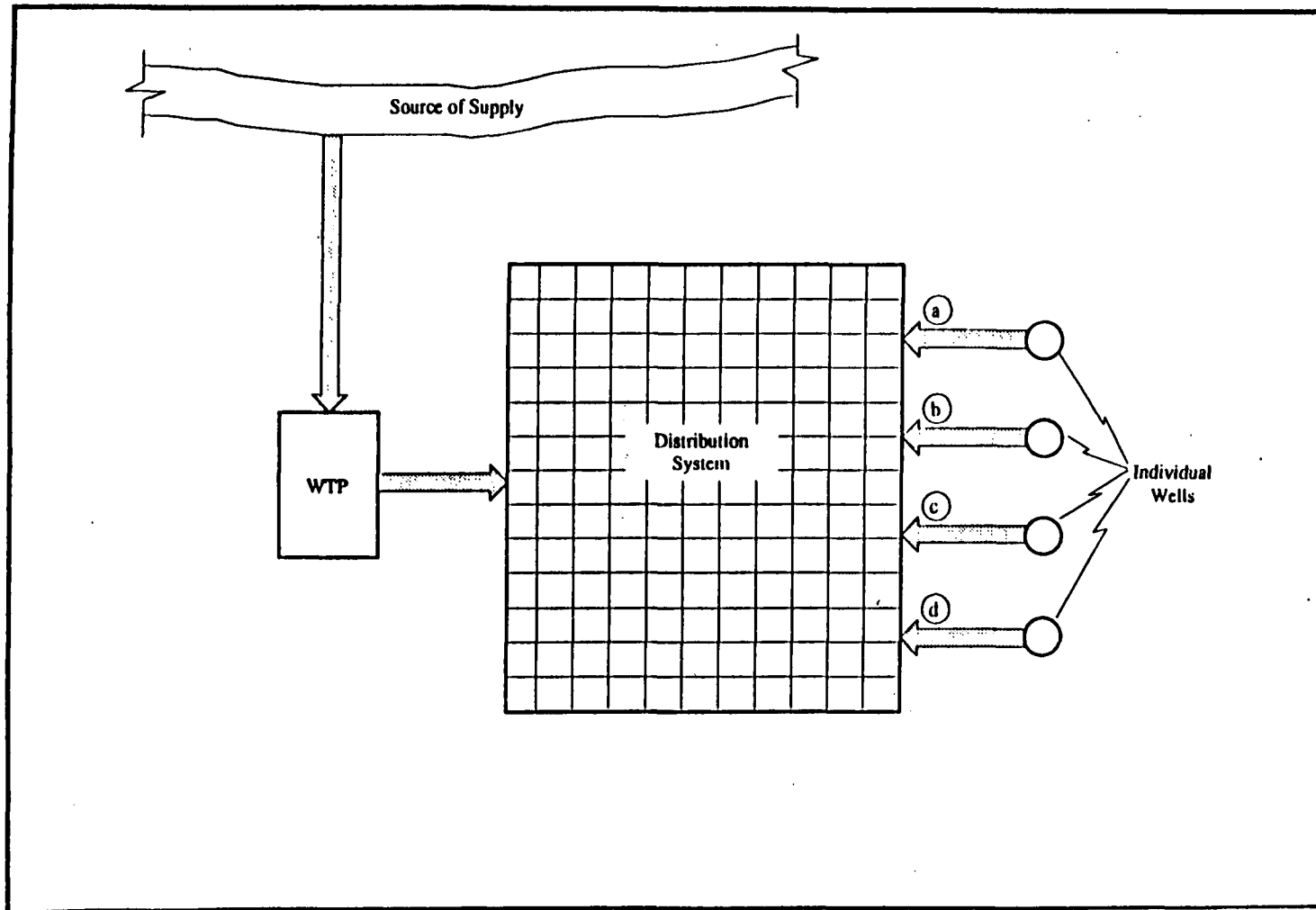


Figure 3-10. PWS with Multiple Sources of Supply

## SCREENING OF ALTERNATIVES

in the future. Since calcium carbonate films currently exist in the distribution system, the corrosion control treatment program for the surface water plant was oriented toward maintaining the existing film and providing lead corrosion control protection in areas where no protective film existed (such as some home plumbing environments). The selected treatment was pH/alkalinity adjustment for lead control with supplemental calcium added to the finished water to prevent dissolution of the calcium carbonate film.

### ***3.4.4 Consecutive Systems.***

Fedarry Water Project 4 (the Project) consists of four communities to which the Project supplies potable water as shown in Figure 3-11. Each member community owns and operates their distribution system. The Project initiated and had approved a consolidation agreement whereby the four communities and the Project would be considered a single PWS for purposes of compliance with the LCR. In the consolidation agreement, corrosion control treatment would be required if the monitoring results for the comprehensive service area exceeded an AL. During initial monitoring, the lead AL was met but the copper AL was exceeded with consistently high copper levels found in Community B. The corrosion problem appeared to be limited to this community, since the copper levels in A, C, and D were below the AL in all cases.

The source of supply for the Project is a low alkalinity, pH, and hardness surface water with similar water quality conditions to that presented in Section 3.4.2. However, the Project had implemented pH and alkalinity treatment five years prior

to the promulgation of the LCR to minimize red water complaints occurring within the comprehensive service area. Since that time, the member communities had experienced fewer problems with corrosion-related complaints. Modification of the existing corrosion control program was determined to be needed since the source water lead and copper levels were below detection. The Project considered two approaches to meet the LCR requirements: modify the existing pH/alkalinity adjustment treatment at the water treatment plant (WTP) or implement modified treatment at the master meter location for Community B.

Based on a review of the water quality conditions (using Figure 3-7), the most promising alternative treatments were pH/alkalinity adjustment or corrosion inhibitors, either phosphates or silicates. Since the literature contained mixed results with the use of phosphates for the control of copper corrosion, phosphate inhibitors were eliminated from further consideration. Based on Figure 3-3, further pH/alkalinity adjustment does not appear to present any additional benefit in copper solubility reduction. For these reasons, the use of silicates was determined to provide optimal treatment for controlling copper in Community B. Since silicate feed systems can be easily installed and operated at the storage reservoir located at the master meter for Community B, the Project decided to recommend to the State that silicate inhibitor treatment be installed at this remote location initially. If copper corrosion control was improved and lead levels did not respond adversely, the Project would consider installing the silicate treatment system-wide.

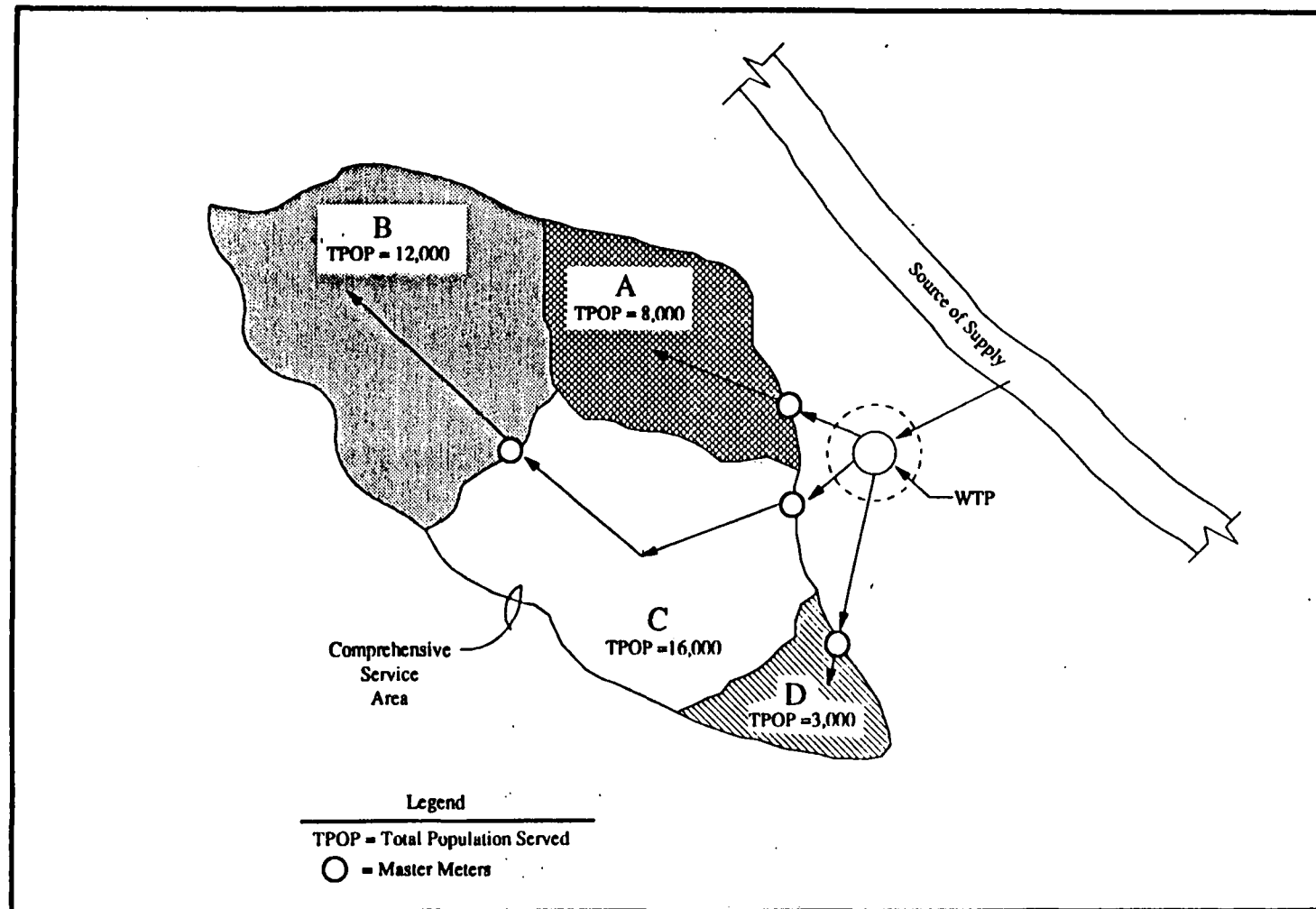


Figure 3-11. Configuration of Consecutive Systems



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## Desktop Evaluation Short Form for Small and Medium PWS Treatment Recommendations

### A. PWS General Information:

<b>1. PWS Identification No.</b>			
<b>2. Contact person:</b>			
Name			
Mailing Address			
Telephone		Fax	
<b>3. Population served</b>			
<b>4. Person responsible for preparing this form:</b>			
Name			
Signature			
Telephone			

### B. PWS Technical Information:

<b>1. Monitoring Results:</b>					
Sampling dates: From _____ To _____					
<b>First-Flush Tap Monitoring Results:</b>					
Lead:					
Minimum concentration	=	_____	mg/L		
Maximum concentration	=	_____	mg/L		
90th percentile	=	_____	mg/L		
Copper:					
Minimum concentration	=	_____	mg/L		
Maximum concentration	=	_____	mg/L		
90th percentile	=	_____	mg/L		
<b>Point-of-Entry Tap Monitoring Results:</b>					
	<b>Points of Entry</b>				
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
Lead Concentration in mg/L:	_____	_____	_____	_____	_____
Copper Concentration in mg/L:	_____	_____	_____	_____	_____
pH:	_____	_____	_____	_____	_____
Temperature, °C:	_____	_____	_____	_____	_____
Alkalinity, mg/L as CaCO <sub>3</sub> :	_____	_____	_____	_____	_____
Calcium, mg/L as Ca:	_____	_____	_____	_____	_____
Conductivity, µmho/cm @ 25°C:	_____	_____	_____	_____	_____
Phosphate, mg/L as P:	_____	_____	_____	_____	_____
Silicate, mg/L as SiO <sub>2</sub> :	_____	_____	_____	_____	_____

**1. Monitoring Results (continued):****Water Quality Parameter Distribution System Monitoring Results:**

Indicate whether field or laboratory measurement.

	Field	Lab
pH: minimum = _____ maximum = _____	_____	_____
alkalinity:	_____	_____
minimum = _____ mg/L as CaCO <sub>3</sub>		
maximum = _____ mg/L as CaCO <sub>3</sub>		
temperature:	_____	_____
minimum = _____ °C		
maximum = _____ °C		
calcium:	_____	_____
minimum = _____ mg/L as Ca		
maximum = _____ mg/L as Ca		
conductivity:	_____	_____
minimum = _____ µmho/cm @ 25°C		
maximum = _____ µmho/cm @ 25°C		
orthophosphate:	_____	_____
(if phosphate-based inhibitor is used)		
minimum = _____ mg/L as P		
maximum = _____ mg/L as P		
silica:	_____	_____
(if silica-based inhibitor is used)		
minimum = _____ mg/L as SiO <sub>2</sub>		
maximum = _____ mg/L as SiO <sub>2</sub>		

**2. Existing Conditions:**

Is treatment used?   yes \_\_\_\_\_   no \_\_\_\_\_

Identify water source(s):

Source No. 1 \_\_\_\_\_

Source No. 2 \_\_\_\_\_

Source No. 3 \_\_\_\_\_

If treatment is used, is more than one source used at a time?

yes \_\_\_\_\_   no \_\_\_\_\_

Identify treatment processes used for each source:

Process	No. 1	No. 2	No. 3
Presedimentation	_____	_____	_____
Aeration	_____	_____	_____
Chemical mixing	_____	_____	_____
Flocculation	_____	_____	_____
Sedimentation	_____	_____	_____
Recarbonation	_____	_____	_____

**2. Existing Conditions (continued):**

Identify treatment processes used for each source:

Process	No. 1	No. 2	No. 3
2nd Stage mixing	_____	_____	_____
2nd Stage flocculation	_____	_____	_____
2nd Stage sedimentation	_____	_____	_____
Filtration:			
Single medium	_____	_____	_____
Dual media	_____	_____	_____
Multi-media	_____	_____	_____
GAC cap on filters	_____	_____	_____
Disinfection:			
Chlorine	_____	_____	_____
Chlorine dioxide	_____	_____	_____
Chloramines	_____	_____	_____
Ozone	_____	_____	_____
Granular Activated Carbon	_____	_____	_____
List chemicals normally fed:			

List chemicals sometimes fed:

**3. Present Corrosion Control Treatment:**

None \_\_\_\_\_

Inhibitor \_\_\_\_\_

Date initiated \_\_\_\_\_

Present dose \_\_\_\_\_

Range in Residual in Distribution System:

Maximum \_\_\_\_\_ mg/L Minimum \_\_\_\_\_ mg/L

Brand name \_\_\_\_\_

Type \_\_\_\_\_

Has it been effective? Please comment on your experience.

pH/alkalinity adjustment \_\_\_\_\_

pH Target \_\_\_\_\_

Alkalinity Target \_\_\_\_\_ mg/L CaCO<sub>3</sub>

Calcium adjustment \_\_\_\_\_

Calcium Target \_\_\_\_\_ mg/L CaCO<sub>3</sub>

**4. Water Quality:**

Complete the table below for typical untreated and treated water quality data. Copy this form as necessary for additional sources. Include data for each raw water source, if surface supplies are used, and finished water quality information (point of entry) from each treatment plant. If wells are used, water quality information from each well is acceptable but not necessary if several wells have similar data. For groundwater supplies, include a water quality summary from each wellfield or grouping of wells with similar quality.

Include available data for the following:

Parameter	Untreated Supply	Treated Water (point of entry)
pH, units		
Alkalinity, mg/L as $\text{CaCO}_3$		
Conductivity, $\mu\text{mho/cm}$ @ 25°C		
Total dissolved solids, mg/L		
Calcium, mg/L Ca		
Hardness, mg/L as $\text{CaCO}_3$		
Temperature, °C		
Chloride, mg/L		
Sulfate, mg/L		

**5. Distribution System:**

Does the distribution system contain lead service lines?

yes \_\_\_\_\_ no \_\_\_\_\_

If your system has lead service lines, mark below the approximate number of lines which can be located from existing records.

None \_\_\_\_\_ Some \_\_\_\_\_ Most \_\_\_\_\_ All \_\_\_\_\_

Is the distribution system flushed?

None \_\_\_\_\_ Some \_\_\_\_\_ Most \_\_\_\_\_ All \_\_\_\_\_

**6. Historical Information:**

Is there a history of water quality complaints?

yes \_\_\_\_\_ no \_\_\_\_\_

If yes, then answer the following:

Are the complaints documented? yes \_\_\_\_\_ no \_\_\_\_\_

Mark the general category of complaints below. Use:

- 1 for some complaints in this category
- 2 for several complaints in this category
- 3 for severe complains in this category

Categories of complaints:

Taste and odor \_\_\_\_\_

Color \_\_\_\_\_

Sediment \_\_\_\_\_

Other (specify) \_\_\_\_\_

Have there been any corrosion control studies?

yes \_\_\_\_\_ no \_\_\_\_\_

If yes, please indicate:

Date(s) of study From \_\_\_\_\_ To \_\_\_\_\_

Study conducted by PWS personnel? yes \_\_\_\_\_ no \_\_\_\_\_

Brief results of study were:

(optional) Study results attached yes \_\_\_\_\_ no \_\_\_\_\_

Were treatment changes recommended? yes \_\_\_\_\_ no \_\_\_\_\_

If yes:

Were treatment changes implemented? yes \_\_\_\_\_ no \_\_\_\_\_

Have corrosion characteristics of the treated water changed? yes \_\_\_\_\_ no \_\_\_\_\_

If yes, how has change been measured?

General observation \_\_\_\_\_

Coupons \_\_\_\_\_

Frequency of complaints \_\_\_\_\_

Other \_\_\_\_\_

Briefly indicate, if other:

**7. Treatment Constraints:**

Optimal corrosion control treatment means the corrosion control treatment that minimizes the lead and copper concentrations at users' taps while insuring that the treatment does not cause the water system to violate any national primary drinking water regulations. Please indicate below which constraints to treatment will apply to your PWS. Use the following code:

- 1 Some constraint = Potential Impact but Extent Is Uncertain
- 2 Significant constraint = Other Treatment Modifications Required to Operate Option
- 3 Severe constraint = Additional Capital Improvements Required to Operate Option
- 4 Very severe constraint = Renders Option Infeasible

Constraint	Treatments			
	pH/Alkalinity Adjustment	Calcium Adjustment	Inhibitor	
			PO <sub>4</sub>	Si
<b>A. Regulatory</b>				
SOCs/IOCs				
SWTR: Turbidity				
Total Coliforms				
SWTR/GWDR: Disinfection				
Disinfection Byproducts				
Lead and Copper Rule				
Radionuclides				
<b>B. Functional</b>				
Taste & Odor				
Wastewater Permit				
Aesthetics				
Operational				
Other				



**8. Desktop Evaluation:**

Briefly summarize the review of the corrosion control literature that pertains to your PWS. A report or summary can be appended to this form if preferred.

Were other similar facilities located which are experiencing successful corrosion control?    yes \_\_\_\_\_    no \_\_\_\_\_

If yes, identify their corrosion control treatment method.

None \_\_\_\_\_  
pH/Alkalinity adjustment \_\_\_\_\_  
Calcium adjustment \_\_\_\_\_  
Inhibitor \_\_\_\_\_  
    Phosphate based \_\_\_\_\_  
    Silica based \_\_\_\_\_

**9. Recommendations:**

The corrosion control treatment method being proposed is:

pH/Alkalinity adjustment \_\_\_\_\_  
    Target pH is \_\_\_\_\_ units  
    Target alkalinity is \_\_\_\_\_ mg/L as  $\text{CaCO}_3$   
Calcium adjustment \_\_\_\_\_  
    Target calcium concentration is \_\_\_\_\_ mg/L Ca  
Inhibitor \_\_\_\_\_  
    Phosphate based \_\_\_\_\_  
        Brand name \_\_\_\_\_  
        Target dose \_\_\_\_\_ mg/L  
        Target residual \_\_\_\_\_ mg/L orthophosphate as p  
    Silica based \_\_\_\_\_  
        Brand name \_\_\_\_\_  
        Target dose \_\_\_\_\_ mg/L  
        Target residual \_\_\_\_\_ mg/L as  $\text{SiO}_2$

Rationale for the proposed corrosion control treatment is:

Discussed in the enclosed report \_\_\_\_\_  
Briefly explained below \_\_\_\_\_

List your proposed operating guidelines:

<u>Parameter</u>	<u>Operating Range</u>
------------------	------------------------

Briefly explain why these guidelines were selected.

10. Please provide any additional comments that will assist in determining optimal corrosion control treatment for your PWS.

## **Chapter 4.0 — Corrosion Control Demonstration Testing**

This chapter is intended primarily for large systems and those small and medium-size systems required by the State to conduct corrosion control studies. Those small and medium-size systems that are not required by the State to conduct corrosion control studies should proceed to Chapter 5 after making their treatment recommendation.

The Rule requires corrosion control studies to be performed by large PWSs and those small and medium-size PWSs required by the State after exceeding the lead or copper AL. Further, the Rule defines certain conditions which must be met by these studies, but it does not specify the details of those studies. This chapter provides guidance for and discusses the following aspects of corrosion control studies: (1) the components necessary to accomplish the study; (2) the testing protocols to be used; (3) the procedures for evaluating data; and (4) the basis for identifying "optimal" corrosion control treatment.

The full scope of a corrosion study will vary system-by-system, and the methods and procedures used to reach a recommendation will necessarily reflect this level of site-specificity. Thus, States should consider the following criteria in the review of corrosion control studies and subsequent recommendations:

- Reasonableness of the study design and findings;

- Technical integrity of the data handling and analysis procedures; and
- Best professional judgement of the State regarding the decision-making criteria used by the PWS in determining the recommended optimal corrosion control treatment.

In the course of this chapter, examples of corrosion control studies will be presented to illustrate the approach and rationale used in the design, implementation, and interpretation of findings for corrosion control studies. A summary of those studies available in the literature is provided in Appendix B for additional resource material available to States, PWSs, and engineers involved in performing corrosion control studies.

### ***4.1 Corrosion Study Organization***

The suggested framework for a corrosion study as shown in Table 4-1 presents a logical sequence of steps, organized to satisfy the requirements and recommendations outlined. For completing steps 1-3, a logic diagram was presented in Section 3.3.1 (Figure 3-6) and these steps refer to the desk-top evaluation discussed at length in Chapter 3. The result of the desk-top evaluation for those systems performing corrosion control studies is the selection of alternative treatments to be tested. Small and medium-size PWSs which are

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**Table 4-1. Organization of the Major Components in Corrosion Control Studies**

<b>Step 1</b>	<b>DOCUMENT HISTORICAL EVIDENCE</b> <ul style="list-style-type: none"> <li>• Review PWS Water Quality and Distribution System Characteristics.</li> <li>• Review PWS Evidence of Corrosion Activity.</li> <li>• Identify Prior Corrosion Control Experiences and Studies Performed by PWS.</li> <li>• Identify Prior Corrosion Control Experiences and Studies Performed by Other PWSs with Similar Characteristics.</li> </ul>
<b>Step 2</b>	<b>EVALUATE SOURCE WATER CONTRIBUTION</b> <ul style="list-style-type: none"> <li>• Monitor Pb/Cu-POE.</li> <li>• Determine Pb/Cu Contributed Due to Corrosion.</li> <li>• Determine Source Water Treatment Needs.</li> </ul>
<b>Step 3</b>	<b>IDENTIFY CONSTRAINTS</b> <ul style="list-style-type: none"> <li>• Compatibility with Water Quality Characteristics (See Figure 3-7).</li> <li>• Interferences with Other Water Treatment Processes.</li> <li>• Compatibility of Multiple Sources of Supply.</li> <li>• Compatibility for Consecutive PWSs.</li> <li>• Reliability Features for Particular Treatment Approach, Including (1) Process Control; (2) Operational Redundancy Requirements; and (3) Chemical Supply Integrity and Availability.</li> <li>• Adverse Impacts on the Community: Commercial Users, Wastewater Operations, Health-Care Facilities.</li> </ul>
<b>Step 4</b>	<b>IDENTIFY CORROSION CONTROL TREATMENT PRIORITIES</b> <ul style="list-style-type: none"> <li>• Targeted Materials for Corrosion Control Protection.</li> <li>• Competing Water Quality/Treatment Objectives.</li> <li>• Secondary Benefits (i.e., Lowering Metal Content in POTW Sludges).</li> </ul>
<b>Step 5</b>	<b>ELIMINATE UNSUITABLE APPROACHES BASED ON FINDINGS FROM STEPS 1-4.</b>
<b>Step 6</b>	<b>EVALUATE VIABLE ALTERNATIVE TREATMENT APPROACHES:</b> <ul style="list-style-type: none"> <li>• Apply Findings from Analogous System Experiences.</li> <li>• Evaluate Alkalinity and pH Adjustment: Reductions in Theoretical Lead and Copper Solubility.</li> <li>• Evaluate Inhibitor Addition: Reductions in Theoretical Lead and Copper Solubility.</li> <li>• Evaluate Calcium Hardness Adjustment: Optimize Calcium Carbonate Precipitation Potential (CCPP).</li> </ul>
<b>Step 7</b>	<b>DECISION:</b> <b>For any PWSs NOT Required to Perform Testing to Evaluate Alternative Treatments:</b> <ul style="list-style-type: none"> <li>• Formulate Decision Criteria.</li> <li>• Select Primary Treatment Alternatives.</li> <li>• Go to Step 9.</li> </ul> <b>For any PWS Required to Perform Demonstration Testing to Evaluate Alternative Treatments:</b> <ul style="list-style-type: none"> <li>• Formulate Minimum Feasibility Criteria for Alternative Treatments.</li> <li>• Select the Alternative Treatments to be Included in the Testing Program.</li> <li>• Establish Decision Criteria to Select Optimal Corrosion Control Treatment.</li> </ul>
<b>Step 8</b>	<b>PERFORM CORROSION CONTROL DEMONSTRATION TESTING.</b> <ul style="list-style-type: none"> <li>• Design Testing Apparatus.</li> <li>• Develop Testing Protocols and Procedures.</li> <li>• Perform Testing Program and Collect Data.</li> <li>• Analyze Data Generating Corrosion Control Performance Results.</li> <li>• Rank Performance Results by Priority of Corrosion Control Program Goals.</li> </ul>
<b>Step 9</b>	<b>PRELIMINARY COST ESTIMATES AND FACILITY MODIFICATIONS.</b> <ul style="list-style-type: none"> <li>• Prepare Preliminary Facility Design.</li> <li>• Prepare Preliminary Cost Estimate.</li> </ul>
<b>Step 10</b>	<b>DECISION:</b> Based on the Decision Criteria Established at the Outset, Formulate <b>RECOMMENDED CORROSION CONTROL TREATMENT</b> AND SUBMIT TO THE STATE.

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not required to perform demonstration testing would select the recommended treatment based on a desk-top evaluation as shown in Figure 3-6.

A corrosion control demonstration testing program is to be formulated and implemented once alternative treatments have been selected. This includes such steps as:

- developing testing protocols, procedures and frequency for data collection and evaluation;
- analyzing the resultant data to generate performance measurements; and
- determining the performance ranking of the alternative treatment approaches on the basis of corrosion control, secondary treatment impacts, and process operations and control.

Preliminary design and cost estimates are to be prepared for the alternative treatments selected from the desk-top evaluation. While cost is not directly a factor in assigning optimal treatment, it may be decisive when alternative treatments have comparable performance. Additionally, preliminary design will be required for the State review process.

The final recommendation of optimal corrosion control treatment may be based on the results of a decision criteria matrix and the ranking of the alternative treatments. The selection process should be documented and presented to the State.

### ***4.2 Overview of Demonstration Testing***

The evaluation of corrosion control treatment through demonstration testing

may be accomplished through a variety of approaches and mechanisms. While flexibility exists for the actual design of a testing program, all such endeavors should clearly define and document the following elements of the study:

- *Testing protocols*, including sampling program design which incorporates sampling frequency, locations, volume, parameters, and analytical methods; and, methods of material exposure such as flow-through or static environments under predetermined operating conditions.
- *Materials used to simulate the targeted piping environment* whether lead, copper, iron, lead soldered joints, brass, etc;
- *Measures of corrosion activity*, such as weight-loss, metal leaching, corrosion rates, and surface condition inspections;
- *Data handling and analysis techniques*, including statistical testing and guidelines for interpreting the findings;
- *Testing of secondary impacts* to determine the potential effects of alternative treatments on existing PWS operations and compliance with other drinking water standards; and
- *Quality assurance/quality control program* elements for each element of the testing program.

The premise underlying demonstration testing is that alternative treatment approaches are to be evaluated in terms of their relative reductions (or increases) in corrosion activity for specific materials of concern. Quite often, testing efforts are used to predict the behavior of various treatment components. In this respect, corrosion studies differ. EPA does not

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consider the purpose of these studies to either: (1) predict the levels of lead or copper in first-draw tap samples from targeted consumers' homes; or (2) predict the actual reductions in corrosion activity within the distribution or home plumbing systems achievable through corrosion control treatment. Instead, the purpose of corrosion control testing is to **demonstrate** the relative performance of alternative treatment approaches and identify optimal treatment.

In order to determine the relative performance of alternative treatment approaches, a control condition must be clearly defined throughout the testing program. Some PWSs may find this problematic due to changing source and treated water conditions. Systems anticipating new sources of supply or new treatment process for existing sources will have to address the issue of which treated water condition to use for its experimental control. For example, a groundwater system required to perform demonstration testing currently provides water treated only with chlorination prior to its delivery. As a result of the SWTR, the well water will be considered as under the influence of a surface water and coagulation and filtration treatment will be required. The anticipated timeframe for completing construction of the new filtration plant is mid-1995. Meanwhile, the demonstration testing program must be concluded by July 1994, prior to the new treated water being available. In this instance, the PWS should consider the water quality modifications anticipated as a result of coagulation and filtration (i.e., pH and alkalinity reductions as a result of alum addition) to determine whether the existing supply would be

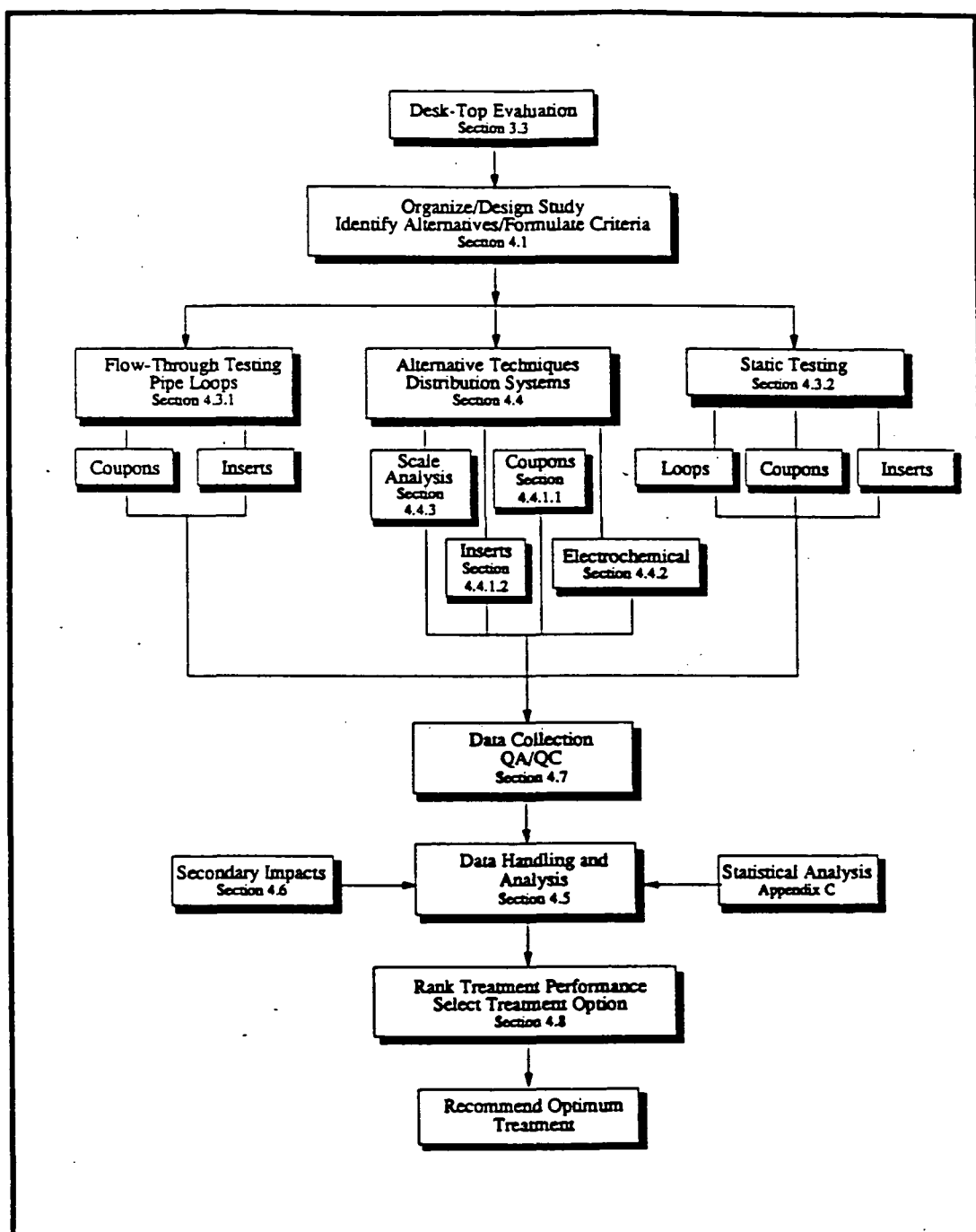
adequately representative of future conditions. For systems introducing new sources of supply to the distribution system, the control condition should be the existing supply and the recommended treatment should include provisions for compatible treatment of the new supply sources. The water delivered under normal operating conditions should serve as the control supply source for those PWSs that experience fluctuations in water quality either seasonally or due to the alternate use of wells.

Each PWS will be responsible for the design and execution of a testing program which meets its specific overall goals and objectives.

### *4.3 Testing Protocols*

Testing protocols should be clearly delineated prior to initiating the demonstration testing program. Some time will need to be allocated for trouble-shooting the methods and procedures to be used. Quite often, a trial-and-error process is required to fully "de-bug" the protocols and establish a consistent monitoring, operating, and maintenance plan for the testing program. Figure 4-1 is included to assist in logically developing and successfully completing a corrosion control study. As can be seen from the diagram, several different pathways are available enroute to selecting optimum corrosion control treatment. Some studies may be designed to select more than one component, i.e., it would not be unusual for both coupons and pipe inserts to be evaluated within a single pipe loop, for example. Section numbers have been added to the diagram to assist the user in selecting which

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**Figure 4-1. Logic Diagram for Corrosion Control Demonstration Testing**

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specific sections of the Guidance Manual should be utilized. It is not necessary, for instance, to read through Section 4.4.2 if electrochemical techniques are not used.

### **4.3.1 Flow-Through Testing Protocols.**

The use of flow-through testing methods to evaluate corrosion control performance is preferred since it more accurately simulates the home plumbing which is the major source of lead and copper. The following suggestions on flow-through testing protocols and methods should be considered by PWSs in the design and execution of their demonstration study.

**4.3.1.1 General.** Flow-through testing refers to continuous or cycled flowing conditions through a testing apparatus where the solution is not recirculated. Typically, flow-through testing is used to describe pipe rig operations where pipe loops or coupon/insert apparatus are attached to a central manifold which distributes the test water to one or more corrosion testing units, as shown in Figure 4-2. Detailed descriptions of standardized pipe rig construction and implementation may be found in either the AWWARF *Lead Control Strategies Manual* (1990a) or the Army Corps of Engineers Pipe Loop (CERL, 1989), including complete material and fabrication specifications.

The following recommendations regarding the design and implementation of a flow-through testing program should be considered when conducting such studies:

- Duration of testing should be between 9 and 15 months to ensure that steady-

state conditions have been achieved and to capture seasonal effects; the longer the testing period, the more confidence a PWS may have in distinguishing treatment performance.

- A standardized sampling program should be established before initiating the testing period to enhance the analysis of results (See Section 3.3.3).
- Alternative locations for siting the testing apparatus should be considered: (a) laboratory or water treatment plant; (b) remote within the distribution system; or (c) distribution system *in situ* apparatus. PWSs should avoid those sites where excess vibration or humidity may be encountered as these conditions can interfere with the performance of the testing apparatus.
- Evaluation of the test material surfaces may be done at the conclusion of each test run for each material in order to assess the corrosion behavior of the treatment alternative. However, this would require the destruction of the test materials, which may be undesirable if future or on-going operation of the testing equipment is anticipated.
- When first-draw samples are being collected, the samples should be drawn slowly to minimize velocities and turbulence within the test apparatus. If air is entrained during sampling, then the sampling velocity is most likely to high.
- Water quality parameters, inhibitor residuals (if appropriate), and metals (lead and copper) should be sampled at each pipe loop (first-draw samples) and the water supply's entrance to each pipe rig.



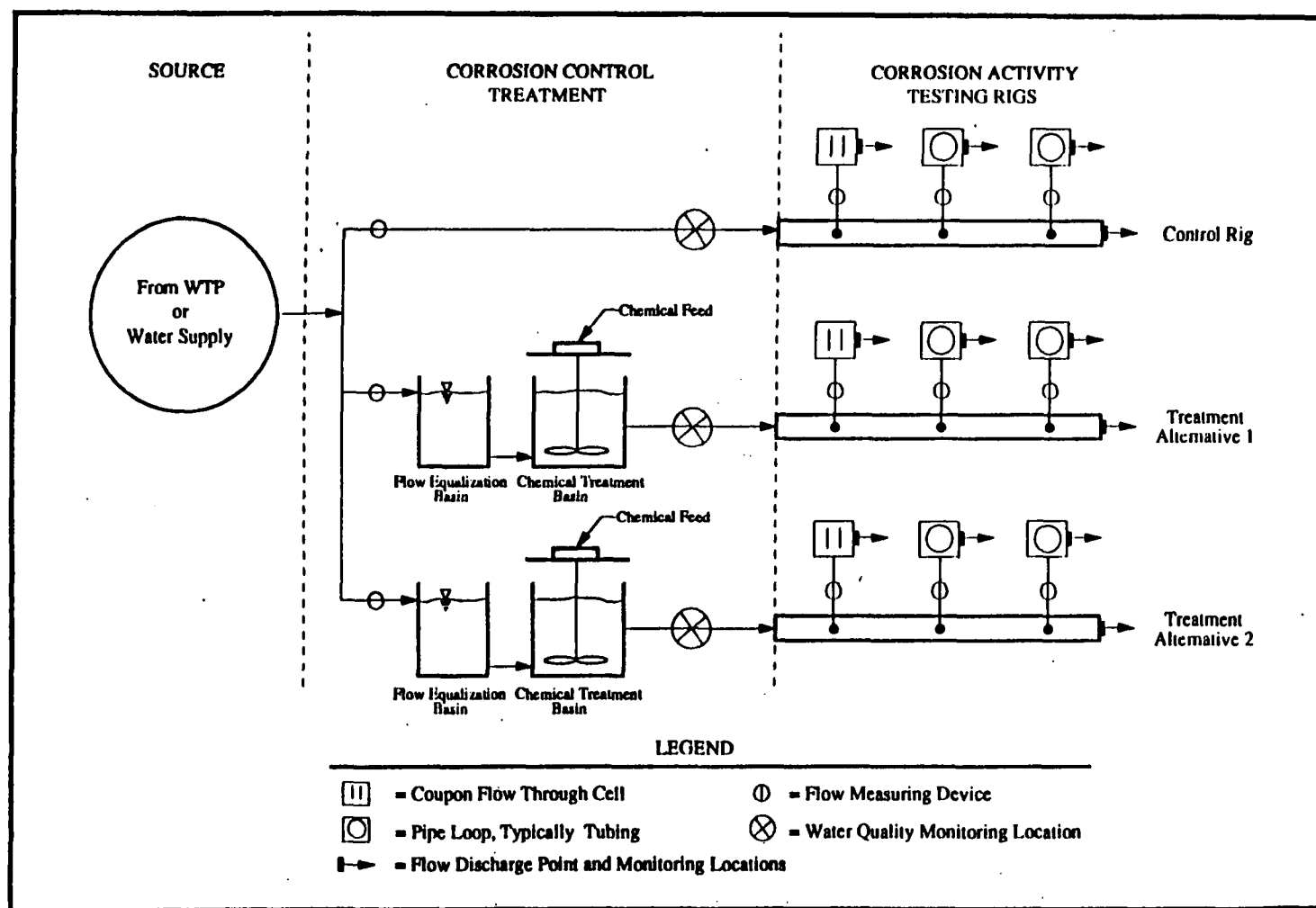


Figure 4-2. Conceptual Layout of Flow-Through Testing Schemes

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- To the extent practical, the test conditions should simulate the chemical feed application points and finished water quality conditions expected during full-scale operations.

Flow-through testing methods provide the following advantages and disadvantages for determining corrosion control treatment. Several of these have been discussed by Schock (1990b):

### **Advantages:**

- The corrosion can be measured on the pipe instead of relying solely on coupons inserted within the pipe.
- Loops can be placed at various locations within the distribution system to assist in determining differing corrosion rates as water quality changes in the system.
- Multiple loops can be set up in a single location to determine the corrosion effects of dissimilar waters.
- The method allows corrosion rates and treatment techniques to be evaluated under controlled conditions. Chemical feed rates can be refined to facilitate defining optimal corrosion control treatment.
- Using pipe loops is fairly economical.
- Pipe loop systems can include provisions for intermittent flow which should simulate "real-world" conditions more appropriately than static testing techniques.

### **Disadvantages:**

- Pipe loops need to be operated for several months before an accurate comparison between differing treatment techniques can be obtained.

- Variations in corrosion rates that occur during the testing period are not measured.
- Dynamic testing systems may require more attention than a static testing apparatus.

An important feature of this method of testing is the in-line corrosion control treatment of the water. This requires some degree of pretreatment components, such as chemical feed pumps, flow equalization basins, flowmeters, and water quality sampling stations. In some cases, the operation and control of the corrosion control treatment component of the test rig may be more complicated than operating and monitoring the pipe rig itself. Careful attention to the feasibility of creating a "continuous" supply of treated water should be addressed prior to any final testing decisions.

PWSs may be able to utilize the flow-through testing system on a long-term basis to assist in understanding the corrosion response of the distribution system. Relationships between the flow-through testing system and the metal levels found in first-draw tap samples may be developed in terms of trends in responses to treatment conditions. Calibration of the flow-through testing system to first-draw tap samples necessitates concurrent flow-through testing and first-draw sampling activity beyond the initial monitoring period. The AWWARF Pipe Loop Study (Kawczynski, 1992) [Note: Expected publication date is early 1993. Available from AWWARF, Denver, CO] presents a testing program designed to evaluate the predictive capability of pipe loop systems in simulating first-draw lead and copper levels in targeted homes. Continued

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utilization of the flow-through testing systems could provide PWSs with an additional mechanism to determine the potential effects of treatment changes on the full-scale level.

### **4.3.1.2 Testing program elements.**

The design and operation of a flow-through testing program requires special consideration of several study components which are briefly discussed below to assist in directing PWSs and others performing such studies. Conducting successful testing programs is dependent on systems making the commitment to sufficiently staff the testing effort, including apparatus design, fabrication, and operation for the duration of the testing program. This resource commitment will be significant. For example, a one-year testing program could require allocation of a full-time operator responsible for fabrication, maintenance, operation, and sampling; as well as analytical support for metals and water quality parameter analyses.

**4.3.1.2.1 Pipe rig operation and fabrication.** The required flow rate through a pipe rig depends on the number of connections it is supplying. Typically, between 0.5 and 2 gallons per minute (gpm) of flow through a single pipe loop is adequate. If a pipe rig consists of two or three loops, then at least 1.5 to 6 gpm of flow is required. Operating a rig at much higher flow rates could compromise its feasibility depending on the complexity of the pretreatment component. For example, a system feeding 20 mg/L soda ash ( $\text{Na}_2\text{CO}_3$ ) for alkalinity and pH adjustment and operating a 6 gpm testing rig for 16 hours of continuous flow with 8 hours of standing time each day would

require 29-gallons of stock solution (20 mg  $\text{Na}_2\text{CO}_3$ /mL). Daily stock solution requirements much beyond 30-gallons becomes difficult to handle, especially when extremely concentrated solutions are used.

Additional attention must be given to the limitations of a slurry feed, such as lime. Analytical grade hydrated lime with a purity exceeding 98 percent is recommended for the preparation of stock solutions (the use of quick lime for testing rigs is not practical due to the large amount of impurities and the inability to properly slake the lime). To avoid plugging pump heads and tubing, solutions more concentrated than 10 mg/mL should not be used. These solutions also require continuous, rigorous mixing during their application in order to ensure a consistent suspension of the slurry solids.

Feeding a corrosion inhibitor with its typically much lower dosages and feed rates is less limiting on the design and operation of the pipe rig system. More flexibility may exist for systems testing corrosion inhibitors in terms of the number of loops, coupons, and inserts a single pipe rig can accommodate. When evaluating silicate inhibitors as a treatment alternative, consideration should be given to providing ample time and dilution for the silicates to depolymerize prior to introduction in a pipe loop system. Silicates in concentrated solutions primarily exist as polymers and break down with time to a monomeric form, which is analogous to the reversion of polyphosphates to orthophosphates. Therefore, if a silicate is injected directly into a pipe loop system, the form of silica present in the pipe loop would be different from the form of silica present in the full-scale distribution

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system. A design of a pipe loop system should include some sort of holding tank to provide adequate detention time and dilution.

The pipe loops attached to the rig should be of sufficient length to permit a sample to be collected without getting water from the central pipe. Pipe loops should be sized to provide at least 15-20 percent additional sample volume to ensure that interferences from other materials in the pipe rig are avoided. Table 4-2 presents the volume of water contained in various lengths of piping by interior diameter dimension. The shaded lines correspond to the minimum length of pipe of the corresponding diameter (the last column shaded) to provide at least 15 percent additional volume in the pipe loop for a one-liter sample. Standard plumbing materials should be used for the pipe loop tubing, and all materials used for each rig should be obtained from the same lot of piping. For example, if copper piping loops are to be used in three different pipe rigs, evaluating three different treatments, then all of the copper used in each rig should be purchased at the same time from the same lot of the manufacturer. Variability in the testing results due to differences in materials can be minimized in this fashion.

For copper loops with lead soldered joints, fabrication of all of the loops should be done by the same person and at one time (do not fabricate one set of loops and then wait several weeks or months before fabricating the next set). Additionally, the solder should come from the same spool. After soldering, the piping should be flushed prior to starting the testing program to remove any loose debris.

In constructing the pipe rig, plastic materials are recommended for all parts that would be in contact with the water except the pipe loops. The use of brass materials should be avoided due to their ability to leach lead and copper into the test water, thereby cross-contaminating the samples and invalidating the test results.

During the startup of the testing program, all pipe loops and the pipe manifold should be flushed to remove any material debris attached to the interior walls of the piping. Flushing should be performed using the control water. The pipe loops should be flushed after fabrication but prior to attachment to the manifold. The complete pipe rig (manifold plus loops) may then be flushed while troubleshooting the apparatus for leaks and the performance of equipment such as flowmeters, timers, valves, and pumps.

Some PWSs may want to incorporate pre-conditioning of the pipe loops into the testing program. Pre-conditioning consists of using control water for all pipe rigs until all pipe loops achieve steady-state corrosion activity. The alternative test waters would then be introduced into the pipe loops for their respective pipe rig system. The relative performance of the control and alternative test conditions would be assessed in the same manner as those testing programs which did not pre-condition the test loops with control water. It is not known whether this step would provide PWSs with any greater accuracy in the evaluation of corrosion control performance, or whether it would reduce or increase the required testing duration.

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**Table 4-2. Pipe Volume by Tubing Length and Diameter**

<b>Pipe Volume Table (Volumes Listed in Liters)</b>						
<b>Pipe Length (Feet)</b>	<b>Pipe Diameter (Inches)</b>					
	<b>3/8</b>	<b>1/2</b>	<b>5/8</b>	<b>3/4</b>	<b>1</b>	<b>1-1/4</b>
1	0.02	0.04	0.06	0.09	0.15	0.24
2	0.04	0.08	0.12	0.17	0.31	0.48
3	0.07	0.12	0.18	0.26	0.46	0.72
4	0.09	0.15	0.24	0.35	0.62	0.97
5	0.11	0.19	0.30	0.43	0.77	1.21
6	0.13	0.23	0.36	0.52	0.93	1.45
7	0.15	0.27	0.42	0.61	1.08	1.69
8	0.17	0.31	0.48	0.69	1.24	1.93
9	0.20	0.35	0.54	0.78	1.39	2.17
10	0.22	0.39	0.60	0.87	1.54	2.41
11	0.24	0.42	0.66	0.96	1.70	2.65
12	0.26	0.46	0.72	1.04	1.85	2.90
13	0.28	0.50	0.78	1.13	2.01	3.14
14	0.30	0.54	0.84	1.22	2.16	3.38
15	0.33	0.58	0.90	1.30	2.32	3.62
16	0.35	0.62	0.97	1.39	2.47	3.86
17	0.37	0.66	1.03	1.48	2.63	4.10
18	0.39	0.69	1.09	1.56	2.78	4.34
19	0.41	0.73	1.15	1.65	2.93	4.58
20	0.43	0.77	1.21	1.74	3.09	4.83
25	0.54	0.97	1.51	2.17	3.86	6.03
30	0.65	1.16	1.81	2.61	4.63	7.24
35	0.76	1.35	2.11	3.04	5.40	8.44
40	0.87	1.54	2.41	3.47	6.18	9.65
45	0.98	1.74	2.71	3.91	6.95	10.86
50	1.09	1.93	3.02	4.34	7.72	12.06
55	1.19	2.12	3.32	4.78	8.49	13.27
60	1.30	2.32	3.62	5.21	9.27	14.48

- Notes:**
1. Volumes can be added together for pipe lengths not listed.
  2. Liters can be converted to gallons by dividing by 3.785.

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In order to collect first-draw sample, the pipe rigs must be operated in a cyclical fashion with water running off and on, permitting a standing time of six-eight hours for the sampling program. The on/off cycles used by a PWS should be consistent throughout the testing program's duration and for each pipe rig under evaluation. Timers may be installed to control the operating cycle of the testing program, or manual operations may be used.

The water entering the pipe rigs should be treated per the operation of the PWS facility. The presence of a disinfectant residual, however, entering the pipe rig may not ensure the absence of biological growth within the testing system. Participants in the AWWARF Pipe Loop Study (Kawczynski, 1992) noted significant growth of heterotrophic plate count (HPC) bacteria at the sample taps in the pipe rigs. To reduce the biological growth, the taps were removed, soaked in a concentrated chlorine solution, and then rinsed prior to being re-attached. Even though the pipe loops and/or manifold may become seeded with bacteria, they should not be superchlorinated or receive excessive dosages of disinfectant as this could affect the steady-state corrosion behavior of the pipe loops.

**4.3.1.2.2 Test monitoring programs.** The sampling program for testing rigs should include: (1) the metals being investigated; (2) water quality parameters defining the treatment process; (3) chemical feed rates and stock solution strengths; (4) water flow rate through each testing apparatus; and (5) sample identification criteria such as test run, date, analyst, time of sampling, sample handling

steps, and location of sample. The frequency of monitoring for specific parameters and the method of sample collection should be defined prior to the initiation of the testing program. Lead and copper samples from the pipe loops should be first-draw sample representing a standing time between six and eight hours. For example, first-draw samples may be collected every two weeks over a 12-month period for metals and water quality parameters representative of tap samples. Daily water quality parameter sampling and recording of the appropriate chemical feed and flow rate measurements may be performed when operating the pipe rig, even though tap samples are not collected, in order to document the water quality conditions to which the test loops are exposed during the study.

### **4.3.2 Static Testing Protocols.**

Static tests may offer an alternative to flow-through pipe loops to ascertain the performance of various treatments with different piping materials (Frey and Segal, 1991). Static testing generally refers to "no flow-through" conditions, or batch testing (for example, jar testing to evaluate coagulant dosages represents a batch testing protocol). The most common form of static testing is immersion testing where a pipe material, typically a flat coupon, is immersed into a test solution for a specified period of time. Corrosion can then be described by weight-loss, metal leaching, or electrochemical measurement techniques. Other static testing methods include: (1) using a pipe segment of the desired material, filling it with test water and measuring the metal pick-up at the conclusion of a specified holding time; and

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(2) recirculation testing where a reservoir of test water is circulated through pipe segments or pipe inserts over a period of time (Note that while water is flowing through the piping segments, it is the same "batch" of water which is being recirculated during the holding time; in this sense, it represents a static test.). These methods have not been widely used, and appropriate test design would be a function of the overall goals and objectives of the testing program.

Static testing procedures do not directly simulate distribution systems. Furthermore, substantial time-savings over flow-through testing methods are not realized with this approach. Single short-term exposure of the metal specimens does not adequately give results about long-term corrosion. Data must be collected for at least nine months before equilibrium conditions are approached and metal leaching has stabilized. Several other critical limitations of static testing are:

- Static testing conditions do not represent the conditions to which piping systems are subject during normal operations. Containers are typically not pressurized and experimental procedures allow the intermittent exposure of containers and coupons/inserts to atmospheric drying. Household plumbing environments experience on-and-off cycles of flow and the distribution system piping network experiences continuous flow-through conditions.
- Exposing coupons and containers to atmospheric conditions, disturbing films on coupons/specimens and containers during replenishing of the containers, evaporation, and other bench-scale

limitations will affect the system water chemistry. Subsequent film formation and metal leaching may not accurately reflect the relative effectiveness of various treatment techniques.

- The variation of test results may confound a PWS's ability to differentiate treatment performance among the alternatives tested. Replicate testing and measurements are important components to the test design in order to provide adequate precision and accuracy.
- Comparability of the test results with full-scale performance is uncertain based on existing information. PWSs may want to place coupons or pipe inserts within the service area and at the POE during the testing program. This would provide a basis of comparison between the static tests (control conditions only) and the full-scale system.

In spite of these disadvantages, some utilities may find static testing useful to screen various potential treatments prior to flow-through testing or full-scale implementation. Static tests may be used to evaluate a greater number of treatment alternatives for a PWS. Time permitting, this procedure could allow a PWS to narrow the treatment approaches to a more limited number for additional flow-through testing, if required. Since flow-through testing programs tend to be more complex and costly, satisfying the demonstration testing needs of a PWS or else eliminating inappropriate treatment alternatives prior to performing flow-through testing would be advantageous. To the extent that static testing may

provide such capabilities, it should be included in the demonstration testing.

As discussed in the previous section on flow-through testing protocols, the testing of silicates as a treatment alternative poses special difficulties. The initial silicate mixture will likely contain polymeric forms which will change over time. This reversion may be partially mitigated by pre-mixing the silicate in a separate container and letting the diluted mixture age for a day or two prior to using.

### **4.4 Alternative Measurement Techniques**

The amount of corrosion may be determined by measuring a number of physical parameters, including weight-loss, metal leaching, corrosion rates, or inspection of surface films and corrosion byproducts. A summary of each of these methods is presented below.

#### **4.4.1 Weight-Loss Measurement Techniques.**

Gravimetric analysis, or weight-loss, is the traditional method of measuring corrosion in the drinking water industry. Many PWSs have placed rectangular coupons or pipe inserts into distribution system mains and service lines to assess corrosion within their system. Figures 4-3 and 4-4 illustrate a typical coupon and pipe insert installation, respectively.

**4.4.1.1 Coupons.** Rectangular coupons can be obtained directly from the manufacturer prepared for installation. Once installed, they are typically exposed for a period of no less than 30-days, and

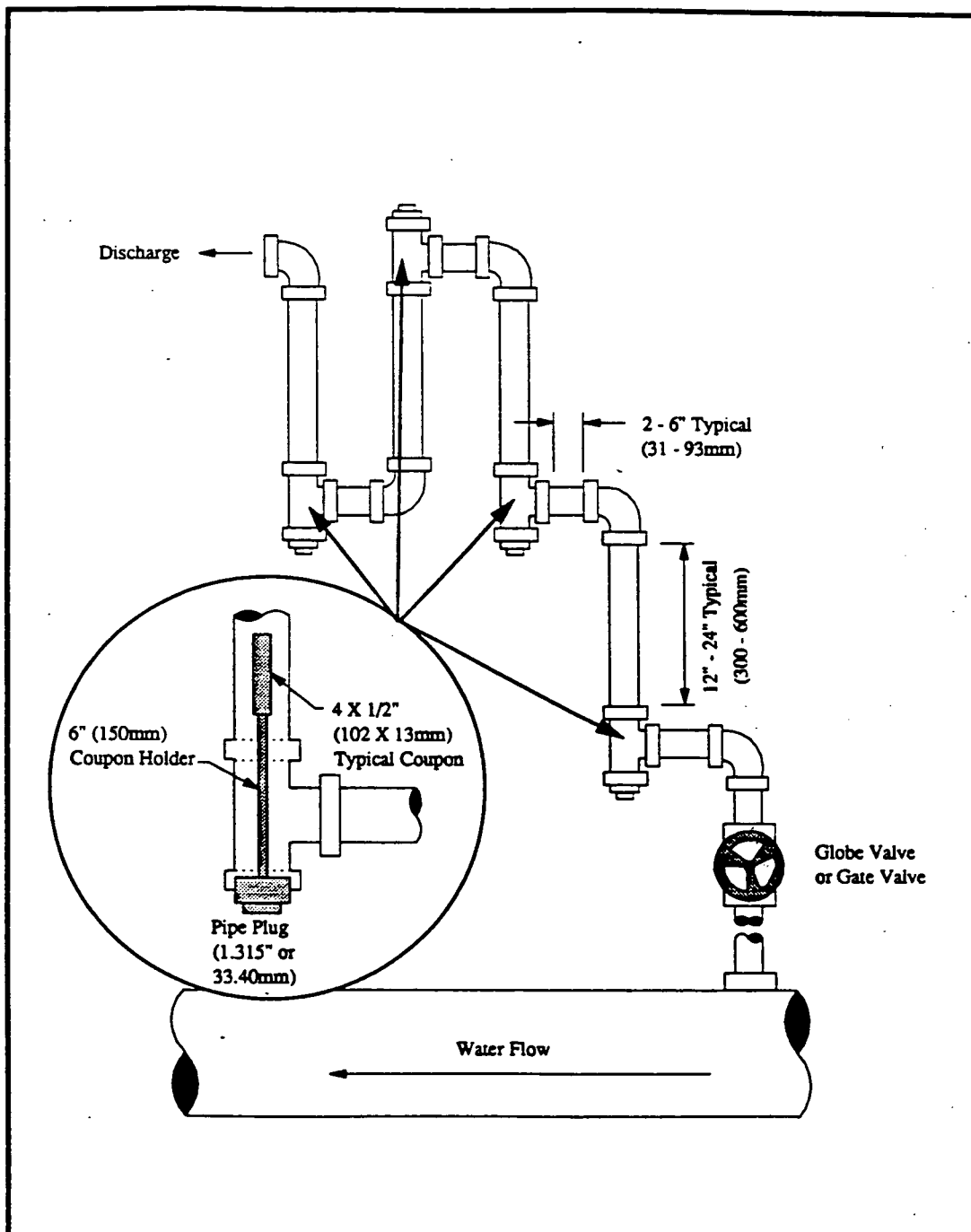
more commonly, for a period of 90 to 180 days. The coupons are then removed, cleaned, and reweighed using specific procedures. In many cases, the coupons can be shipped back to the manufacturer for final preparation and weighing.

Coupon geometry and materials have been standardized by ASTM. Flat coupons typically are made from sheet metal; however, cast iron and cast bronze coupons can be prepared from castings. Coupon sizes should be 13 by 102 by 0.8 millimeters (0.5 by 4.0 by 0.032 inches) for all sheet metals, and 13 by 102 by 4 mm for cast metals. Other sizes may be used provided the total surface area is approximately 258 cm<sup>2</sup> (or 4 in<sup>2</sup>). A 7-mm hole is punched through the coupon such that its center is approximately 8-mm from one end of the coupon. The coupons are then smoothed and stamped with an identification number between the edge and the mounting hole in order to track the results.

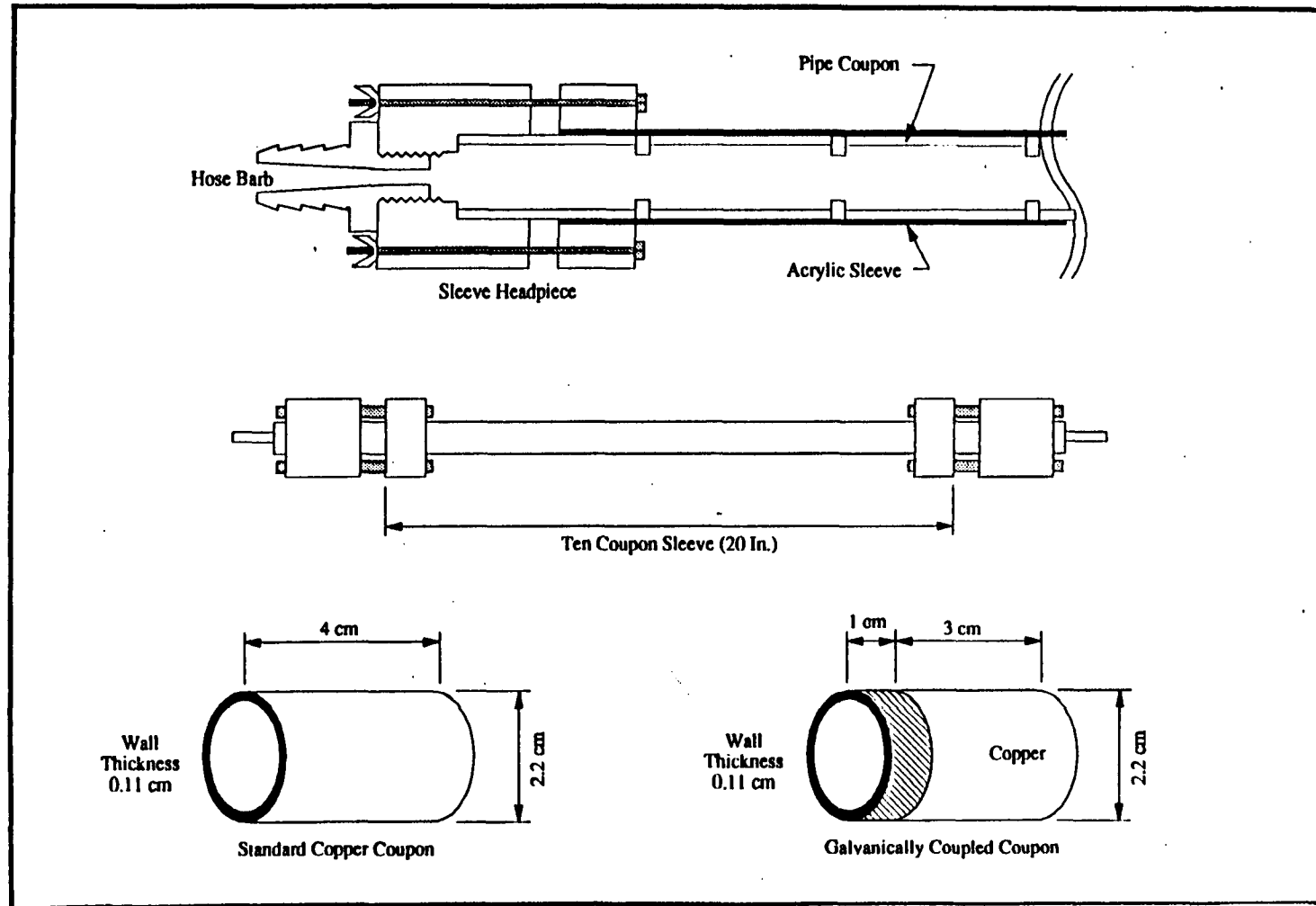
Table 4-3 lists the ASTM material specifications for coupons by the metal alloy and its reference number (ASTM 1990, G-1). ASTM has standard protocols for coupon preparation for weight-loss experiments with water (ASTM 1990, D-2688). These protocols can be obtained directly from ASTM or at most technical libraries. ASTM references are used throughout the industry regarding the application and handling of mild steel, copper, and galvanized coupons. Tables 4-4 and 4-5 summarize the cleaning procedures for the coupons after they have been exposed to the test environment for the required period of time.



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**Figure 4-3. Typical Coupon Testing Installation**



**Figure 4-4. Typical Pipe Coupon Insert Installation**  
From Wysock et al. 1991

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**Table 4-3. Densities for a Variety of Metals and Alloys**

UNS Number	Stainless Steels	Density (g/cm <sup>3</sup> )
520100	Type 201	7.94
520200	Type 202	7.94
530200	Type 302	7.94
530400	Type 304	7.94
530403	Type 304L	7.94
530900	Type 309	7.98
531000	Type 310	7.98
531100	Type 311	7.98
531600	Type 316	7.98
531603	Type 316L	7.98
531700	Type 317	7.98
532100	Type 321	7.94
532900	Type 329	7.98
N08330	Type 330	7.98
534700	Type 347	8.03
541000	Type 410	7.70
543000	Type 430	7.72
544600	Type 446	7.65
550200	Type 502	7.82
<b>Copper and Copper Alloys - Brass &amp; Bronze</b>		
C38600	Copper	8.94
C23000	Red brass 230	8.75
C26000	Cartridge brass 260	8.52
C44300, 44400, 44500	Admiralty 443, 444, 445	8.52
<b>Aluminum Alloys</b>		
C68700	Aluminum brass 687	8.33
C22000	Commercial bronze 220	8.20
C60800	Aluminum bronze, 5% 608	8.16
*	Aluminum bronze, 8% 612	7.78
*	Composition M	8.45
*	Composition G	8.77
<b>Lead</b>		
L53305-53405	Antimonial	10.80
L5XXXX	Chemical	11.33
<p><b>Note X1.1</b> All UNS numbers that include the letter X indicate a series of numbers under one category.</p> <p><b>Note X1.2</b> An asterisk indicates that a UNS number not available.</p>		

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**Table 4-4. Chemical Cleaning Procedures for Removal of Corrosion Products**

Designation	Material	Solution	Time	Temperature	Remarks
C.2.1	Copper and Copper Alloys	500 mL hydrochloric acid (HCl, sp gr 1.19) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Deaeration of solution with purified nitrogen will minimize base metal removal.
C.2.2		4.9 g sodium cyanide (NaCN) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Removes copper sulfide corrosion products that may not be removed by hydrochloric acid treatment (C.2.1).
C.2.3		100 mL sulfuric acid (H <sub>2</sub> SO <sub>4</sub> , sp gr 1.84) Reagent water to make 1000mL	1 to 3 min	20 to 25° C	Remove bulky corrosion products before treatment to minimize copper redeposition on specimen surface.
C.2.4		120 mL sulfuric acid (H <sub>2</sub> SO <sub>4</sub> , sp gr 1.84) Reagent water to make 1000 mL	5 to 10 s	20 to 25° C	Removes redeposited copper resulting from sulfuric acid treatment.
C.2.5		54 mL sulfuric acid (H <sub>2</sub> SO <sub>4</sub> , sp gr 1.84) Reagent water to make 1000 mL	30 to 60 min	40 to 50° C	Deaerate solution with nitrogen. Brushing of test specimens to remove corrosion products followed by re-immersion for 3 to 4 s is recommended.
C.3.1	Iron and Steel	1000 mL hydrochloric acid (HCl, sp gr 1.19) 20 g antimony trioxide (Sb <sub>2</sub> O <sub>3</sub> ) 50 g stannous chloride (SnCl <sub>2</sub> )	1 to 25 min	20 to 25° C	Solution should be vigorously stirred or specimen should be brushed. Longer times may be required in certain instances.
C.3.2		50 g sodium hydroxide (NaOH) 200 g granulated zinc or zinc chips Reagent water to make 1000 mL	30 to 40 min	80 to 90°C	Caution should be exercised in the use of any zinc dust since spontaneous ignition upon exposure to air can occur.
C.3.3		200 g sodium hydroxide (NaOH) 20 g granulated zinc or zinc chips Reagent water to make 1000 mL	30 to 40 min	80 to 90°C	Caution should be exercised in the use of any zinc dust since spontaneous ignition upon exposure to air can occur.

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**Table 4-4. Chemical Cleaning Procedures for Removal of Corrosion Products (continued)**

Designation	Material	Solution	Time	Temperature	Remarks
C.3.4	Iron and Steel (continued)	200 g diammonium citrate ( $(\text{NH}_4)_2\text{HC}_3\text{H}_5\text{O}_7$ ) Reagent water to make 1000 mL	20 min	75 to 90° C	Depending upon the composition of the corrosion product, attack of base metal may occur.
C.3.5		500 mL hydrochloric acid (HCl, sp gr 1.19) 3.5 g hexamethylene tetramine Reagent water to make 1000 mL	10 min	20 to 25° C	Longer times may be required in certain instances.
C.3.6		Molten caustic soda (NaOH) with 1.5-2.0 % sodium hydride (NaH)	1 to 20 min	370° C	For details refer to Technical Information Bulletin SP29-370. "DuPont Sodium Hydride Descaling Process Operating Instructions."
C.4.1	Lead and Lead Alloys	10 mL acetic acid ( $\text{CH}_3\text{COOH}$ ) Reagent water to make 1000 mL	5 min	Boiling	---
C.4.2		50 g ammonium acetate ( $\text{CH}_3\text{COONH}_4$ ) Reagent water to make 1000 mL	10 min	60 to 70° C	---
C.4.3		50 g ammonium acetate ( $\text{CH}_3\text{COONH}_4$ ) Reagent water to make 1000 mL	5 min	60 to 70° C	---

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**Table 4-5. Electrolytic Cleaning Procedures for Removal of Corrosion Products**

Designation	Material	Solution	Time	Temperature	Remarks
E.1.1	Iron, Cast Iron, Steel	75 g sodium hydroxide (NaOH) 25 g sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) 75 g sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) Reagent water to make 1000 mL	20 to 40 min	20 to 25° C	Cathodic treatment with 100 to 200 A/m <sup>2</sup> current density. Use carbon, platinum or stainless steel anode.
E.1.2		28 mL sulfuric acid ( $\text{H}_2\text{SO}_4$ , sp gr 1.84) 0.5 g inhibitor (diorthotolyl thiourea or quinoline ethylidide or bethanaphthol quinoline) Reagent water to make 1000 mL	3 min	75° C	Cathodic treatment with 2000 A/m <sup>2</sup> current density. Use carbon, platinum or lead anode.
E.2.1	Lead and Lead Alloys	28 mL sulfuric acid ( $\text{H}_2\text{SO}_4$ , sp gr 1.84) 0.5 g inhibitor (diorthotolyl thiourea or quinoline ethylidide or betanaphthol quinoline) Reagent water to make 1000 mL	3 min	75° C	Cathodic treatment with 2000 A/m <sup>2</sup> current density. Use carbon, platinum or lead anode.
E.3.1	Copper and Copper Alloys	7.5 g potassium chloride (KCl) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Cathodic treatment with 100 A/m <sup>2</sup> current density. Use carbon or platinum anode.

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In general, ASTM recommendations are that coupons should be similar in composition to the piping within the system being evaluated. Materials commonly found within water distribution systems include cast iron, ductile iron, galvanized iron, copper, lead, lead/tin solder, mild steel, brass, bronze, asbestos-cement, and plastic. Some of these materials, such as brass and bronze, may be present in household plumbing fixtures and may contain metal impurities such as lead and zinc.

Several advantages and disadvantages of coupon testing are summarized below (Schock, 1990b):

### **Advantages:**

- Provides information on the amount of material undergoing corrosion for a specific set of conditions.
- Coupons can be placed within actual distribution systems.
- The method is relatively inexpensive.

### **Disadvantages:**

- Coupons are generally in the system for 90 to 120 days before data are obtained.
- Variations in corrosion rates within the testing period are not identified.
- Standard coupons may not be representative of the actual material within the system undergoing corrosion.
- The coupon is located within the pipe section. Thus, it may not accurately indicate the corrosion occurring at the pipe wall because the weight-loss may be due to abrasion not corrosion.

- It is difficult to remove corrosion products during analysis without disturbing some of the attached metal.

**4.4.1.2 Pipe inserts.** The first use of piping inserts in lieu of rectangular coupons was developed by T.E. Larson at the laboratories of the Illinois State Water Survey (1975), corresponding to ASTM standard 2688-82 method C. Pipe inserts consist of a short piece of 1-inch diameter tubing of the desired material, inserted into a PVC sleeve and plumbed into a convenient delivery line or laboratory testing equipment.

A modified approach using pipe inserts was presented by Reiber et al. (1988) which permitted multiple inserts within a single assembly and allowed replicate results to be gathered. Additionally, the methods used by Reiber et al. (1988) use only mechanical means of insert preparation and cleaning after exposure which eliminates chemical treatment and acid rinses.

**4.4.1.3 Calculation of corrosion rates.** The difference between the initial and final weights of the coupon or pipe inserts reflects the corrosion activity within the system. This measurement is in mils per year of material-loss or gain.

For most applications, the following equation is sufficiently accurate to estimate the corrosion rate based on coupon testing results:

$$P = [H(W_1 - W_2)/W_1 D] \times 1.825 \times 10^5$$

where, P = corrosion rate, mils per year; H = original thickness of the coupon, inches;  $W_1$  = original weight of the coupon, milligrams;  $W_2$  = final weight of the coupon, milligrams; and D = exposure time,

days. In those cases where more precise control is exerted over all variables defining the test conditions, the corrosion rate for a rectangular coupon may be calculated as follows:

$$P = 1/[1/H + 1/X + 1/Y] \times [(W_1 - W_2)/W_1 D] \times 1.825 \times 10^5$$

where P = corrosion rate, mils per year; H = original thickness of the coupon, inches; X = original length of the coupon, inches; Y = original width of the coupon, inches; W<sub>1</sub> = original weight of the coupon, milligrams; W<sub>2</sub> = final weight of the coupon, milligrams; and D = exposure time, days.

Rates of corrosion using pipe inserts may be calculated as either milligrams per square decimeter per day (mdd) or as mils per year of loss/gain. The method for calculating corrosion rates in mdd is as follows:

For Steel and Galvanized Specimens:  
mdd = 1180 W/T,

For Copper specimens:  
mdd = 1230 W/T,

where W = actual weight loss of the insert, milligrams; and T = installation time, days. To convert mdd to mpy, use the following equation:

$$\text{mpy} = (1.437 \text{ mdd/d})$$

where d = density of the coupon material, grams/cubic centimeter.

## 4.4.2 Corrosion Rates.

Electrochemical methods of determining corrosion rates may also be applied to drinking water systems. The difference in electrostatic potential between a test and reference electrode under applied

current densities can be related to the rate of corrosion reactions. Linear polarization techniques have produced good correlation with weight-loss measurement techniques (Reiber and Benjamin, 1990).

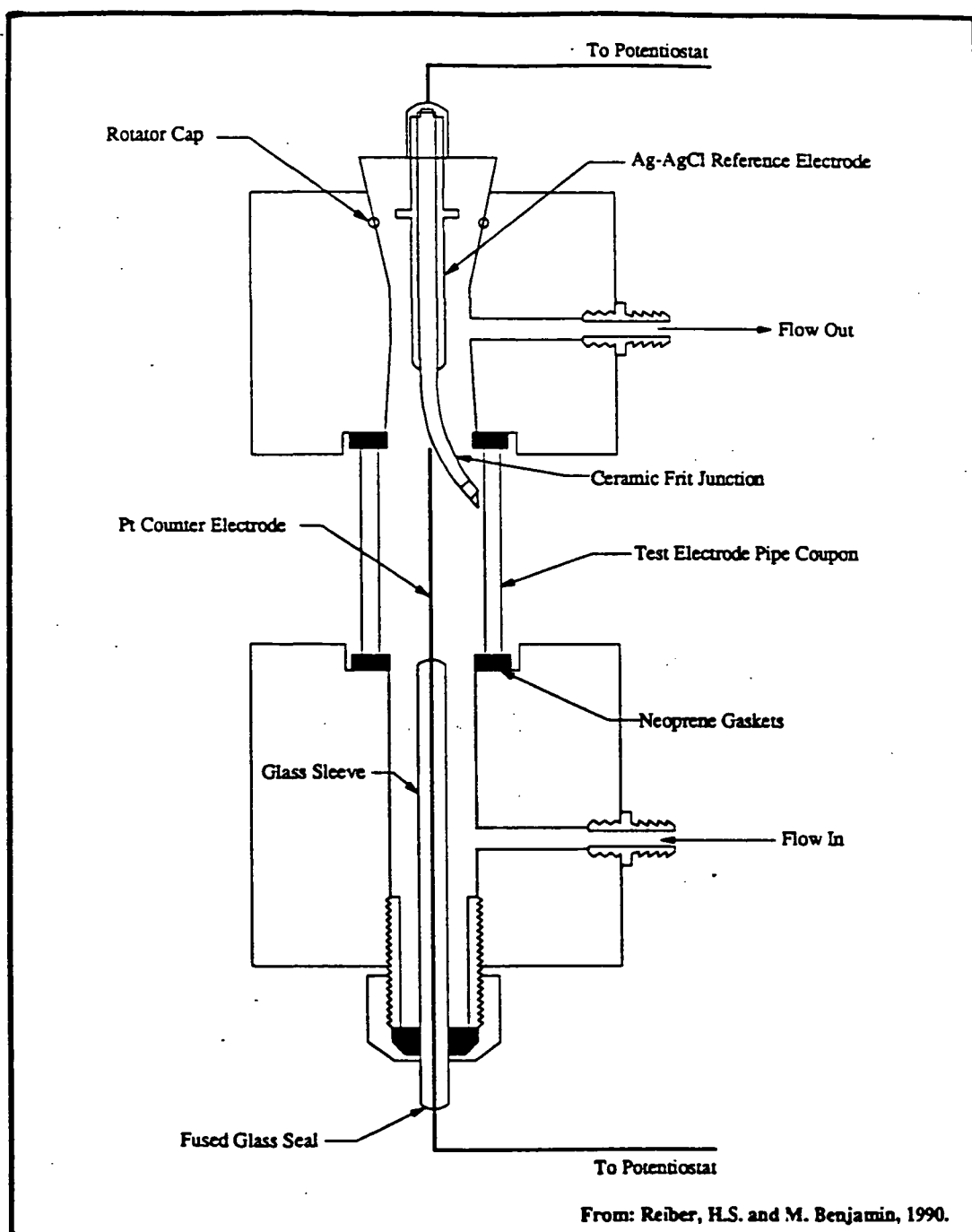
Figure 4-5 illustrates the polarization cell utilized by Reiber and Benjamin (1990). The test electrodes are actual pipe inserts, and can be of materials of interest to the PWS. The cell and its instrumentation can be easily reproduced by PWSs. The investigators felt that their cell design simulated pipe flow conditions which allowed turbulence and scour effects on the corrosion control to be investigated.

## 4.4.3 Surface Inspection.

Visual inspection of piping or coupon surfaces should be performed when possible in all testing programs. The type of corrosion action should be noted, i.e., pitting, uniform corrosion, scale characteristics (continuous, patchy, non-existent), and coloration. Additionally, the scale, if present, may be scraped from the surface of the pipe material and chemically analyzed to determine the key components contained in the scale. This process does not identify the specific chemical compounds composing the scale, but it does indicate the elements which are part of the chemical matrix.

Beyond visual inspection and chemical analyses of scale material, X-ray diffraction techniques may be employed to further identify the scale composition and crystallization characteristics. However, these methods are extremely expensive, and only a few laboratories are capable of performing such tests.





**Figure 4-5. Cross-Section of Polarization Flow Cell**

## 4.5 Data Handling and Analysis

Data needs are an important consideration in the design of the testing program. Analytical procedures should be clearly defined as part of the testing program development to: (1) describe the behavior of the testing data; and (2) generate performance rankings for the alternative treatments. The most useful approach to statistically evaluating corrosion control data involves the application of non-parametric statistics.

Underlying all statistical measures are certain, fundamental assumptions regarding the "true" behavior of the data. Those statistical tests which are most commonly applied (such as the Student-t Test, chi-square distribution, difference of means, analysis of variance) are based on populations of data that are normally distributed. A normally-distributed population will form a bell-shaped curve which is symmetrical about the mean, or average, of the data. Although standard statistical tests developed for a normal population are often used for sets of water quality data, most water quality data do not follow a normally-distributed curve. The reader is referred to Appendix C and statistical reference books for further discussions of this topic.

Corrosion control testing data tend to be non-normal, and therefore, conventional statistical measures may not accurately describe the behavior of the data, or reliably generate results which could be used to rank alternative treatments without modification. The example presented in Section 4.9.1 demonstrates the use of traditional statistical tests using

the skewness coefficient and Student's t test to compare the performance of alternative treatments.

Alternatively, non-parametric analyses accommodate non-normal conditions, and can be applied to develop relative performance measures for numerous treatments. The non-parametric tests of importance are: (1) the Wilcoxon test or U-test which can compare the results of two conditions to determine whether they behave similarly (i.e., no difference in corrosion performance can be ascertained) or whether they behave differently (i.e., one treatment method produces better corrosion protection); and (2) the Kruskal-Wallis test, or H-test, which is the more general case and can evaluate more than two test conditions. Additional information on the application of non-parametric statistics in evaluating demonstration testing data is provided in Appendix C.

The information to be collected for each testing run include descriptions of: (1) the test conditions (run number, treatment dosages of applied chemicals, water quality parameters, and date); (2) sampling event (control versus test apparatus, location of sampling point, time, and type of material); and (3) the analytical results (water quality parameters such as pH, temperature, alkalinity, hardness, inhibitor residual, disinfectant residual, lead, copper, iron, etc. and/or coupon weight conditions).

The use of spreadsheets or database management skills with personal computers will be satisfactory for the analysis of data from most corrosion studies. Computer software, including statistical analysis programs, is generally locally available.

## 4.6 Testing of Secondary Impacts

Testing of secondary impacts is vital to the overall study design for optimal treatment. A primary area of concern for secondary impacts is how the alternative corrosion control treatment may be successfully installed and operated so as to meet future State-mandated operating conditions that define compliance with the Lead and Copper Rule. When pH, alkalinity or calcium adjustment are components of a treatment alternative, the stability of these parameters between the point of adjustment, the POE, and throughout the distribution system should be ascertained. Additionally, the likelihood of inhibitors and key water quality parameters to remain within acceptable limits in the distribution system should be investigated.

Compliance with existing and future drinking water standards must be achieved after the installation of corrosion control treatment. Testing to evaluate these conditions should be included in the design of the corrosion control study. Of particular concern may be changes in: (1) the impact on compliance with the disinfection performance requirements of the SWTR and the up-coming Ground Water Disinfection Rule (GWDR); (2) the levels and types of disinfection byproducts (DBPs) that may occur; (3) the occurrence of positive total coliform events or inducement of confluent growth in total analyses due to increases in heterotrophic plate count bacteria; or (4) disinfectant residual concentrations.

The impact of alternative treatment on compliance capability of current and future regulatory requirements should be

fully explored. Disinfection performance may be determined by applying the CT values and calculation procedures presented in the *SWTR Guidance Manual* (USEPA, 1989) and briefly discussed in Section 3.3.3 of this manual. The regulation of disinfection byproducts will affect all PWSs regardless of the population served. Evaluating the effect of corrosion control treatment alternatives on the formation of total trihalomethanes (TTHMs) and other DBPs can be accomplished during the testing program by generating either rate of formation curves for the key DBPs or simulated distribution system levels of DBPs. PWSs may reference the *AWWA Standard Methods, 17th Edition* (AWWA, 1989) for an analytical method to determine the simulated distribution system total trihalomethane concentration (SDSTTHM).

## 4.7 Quality Assurance/Quality Control Programs

The interpretation of data is founded upon the assurances that proper quality assurance and quality control (QA/QC) procedures were followed during the testing program. A well-designed QA/QC program permits the investigator to more accurately describe the variability introduced into the data by the response of testing materials to the corrosion control treatment processes being evaluated alone. Elements to be included in a QA/QC program include:

- Sufficient sampling frequency for water quality parameters during the period of time when water is flowing to adequately describe the test conditions to which the materials were subject

between first-draw samples. For example, if standing samples are collected each week, then at least daily sampling for water quality parameters should be performed for the treated water supplied to the pipe rig.

- Split samples for metal analyses, especially when metal test kits are being used. EPA recommends that at least five percent of the samples collected be split samples.
- Sample blanks and spikes should be prepared by someone other than the chemical analyst to verify routine measurements. A sample blank and spike should be performed during each testing period for metals.
- Proper calibration of all analytical instruments should be performed at the beginning of each testing period. Chemical feed and flow rate meters should be fully calibrated prior to the initiation of testing and periodically checked during the testing program.
- Sample handling procedures should follow those required in the Rule for metals and water quality parameters. Special care should be given to the cleaning procedures utilized for metals sample containers to minimize cross-contamination between samples.

Each testing program will need to address its specific QA/QC requirements, and should delineate these elements at the beginning in order to prevent the collection of data which cannot be adequately verified.

### ***4.8 Selecting the Recommended Treatment Option***

The factors affecting the selection of a treatment technique include:

- **Performance** of alternative treatments evaluated during demonstration testing for mitigating corrosion based on the prioritization of (a) the targeted materials; (b) the measurement technique used to describe corrosion activity (metal solubility, weight-loss, corrosion rate, etc); and (c) confidence in the testing program results (QA/QC and statistical analysis validity).
- **Feasibility** of implementing the alternative corrosion control treatment.
- **Reliability** features of the alternative treatment approaches based on treated water quality and full-scale operational characteristics.
- **Costs** associated with installation and operation, where alternative treatments have comparable performance.

A decision matrix including each of the above factors may be developed and applied as the basis for selecting the 'optimal' corrosion control treatment. Weighting factors which assign relative priorities should be related to site-specific criteria. In most cases, however, the performance of the alternative treatments in reducing lead and/or copper should receive the greatest priority.

#### ***4.8.1 Example of Treatment Selection.***

A large PWS performed a desk-top evaluation of their system and identified two alternative treatments for further study by

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corrosion testing. Flow-through testing was performed using pipe rigs with: (1) iron tubing and copper tubing with lead solder, and (2) copper, lead, and iron coupon flow-through cells. Figures 4-6A and 4-6B present results of corrosion testing in terms of reductions in metal concentrations for standing samples and average weight-loss for treatment alternatives A and B as compared to the existing treatment.

The first-step in developing the final treatment selection decision matrix is defining the performance ranking of each treatment evaluated. The score for the best treatment option used in this analysis is 7, for second 4, and for the worst option 0. Given the priorities of the PWS, the weighting factors used for each metal were 0.45, 0.40 and 0.15 for lead, copper, and iron, respectively. Due to the increased importance in controlling lead and copper solubility, the weighting factors for measurement technique were 0.7 and 0.3 for metal concentration and weight-loss results, respectively, for lead and copper. For iron, however, the measurement weighting factor was 0.3 and 0.7 for metal concentration and weight-loss results, respectively, due to more concerns about maintenance and repair of iron piping.

Table 4-6 presents the corrosion control performance matrix with the appropriate weighting factors. The resultant score indicates that treatment A provided the best corrosion control protection, while treatment B provided the second best and the existing treatment provided the worst performance. These results are used in the final treatment selection matrix.

Table 4-7 presents the final treatment selection matrix for the PWS. A desk-top evaluation of treatments A and B prior to testing revealed that these treatment options were equally feasible. As a result, feasibility of treatments A and B is not a part of the decision matrix. By far, the most important factor for

identifying optimal treatment in this case is treatment performance, shown by setting its weighting factor at 0.75. The reliability and cost weighting factors were set at 0.15 and 0.10, respectively. The reliability of the treatment options is considered more important than the costs since compliance will eventually be determined by the ability of the PWS to consistently produce finished water which meets its treatment objectives. The costs of treatment should be assigned a low weighting factor (here 0.1) to reflect the fact that costs are not directly relevant to selecting the optimal treatment, except in helping to decide between alternative treatments with comparable performance. Based on the results of the final treatment selection decision matrix, Treatment A would be recommended as optimal corrosion control treatment.

### 4.9 Examples of Corrosion Studies

#### 4.9.1 Flow-Through Testing.

Utility A exceeded the action level for lead during its first 6-month period of diagnostic monitoring and initiated a corrosion control study. The Utility treats water from a surface supply to provide a treated water with the following general characteristics:

pH = 7.8	Total hardness = 85 mg/L as CaCO <sub>3</sub>
SO <sub>4</sub> = 40 mg/L	Ca hardness = 52 mg/L as CaCO <sub>3</sub>
Cl = 5 mg/L	Total alkalinity = 80 mg/L as CaCO <sub>3</sub>
Na = 10 mg/L	Total solids = 275 mg/L

As illustrated on Figure 3-7, several avenues for treatment exist. After conducting a desk top study and visiting with some other utilities using similar water sources, Utility A decided to utilize pipe loops to further define optimal corrosion control treatment.

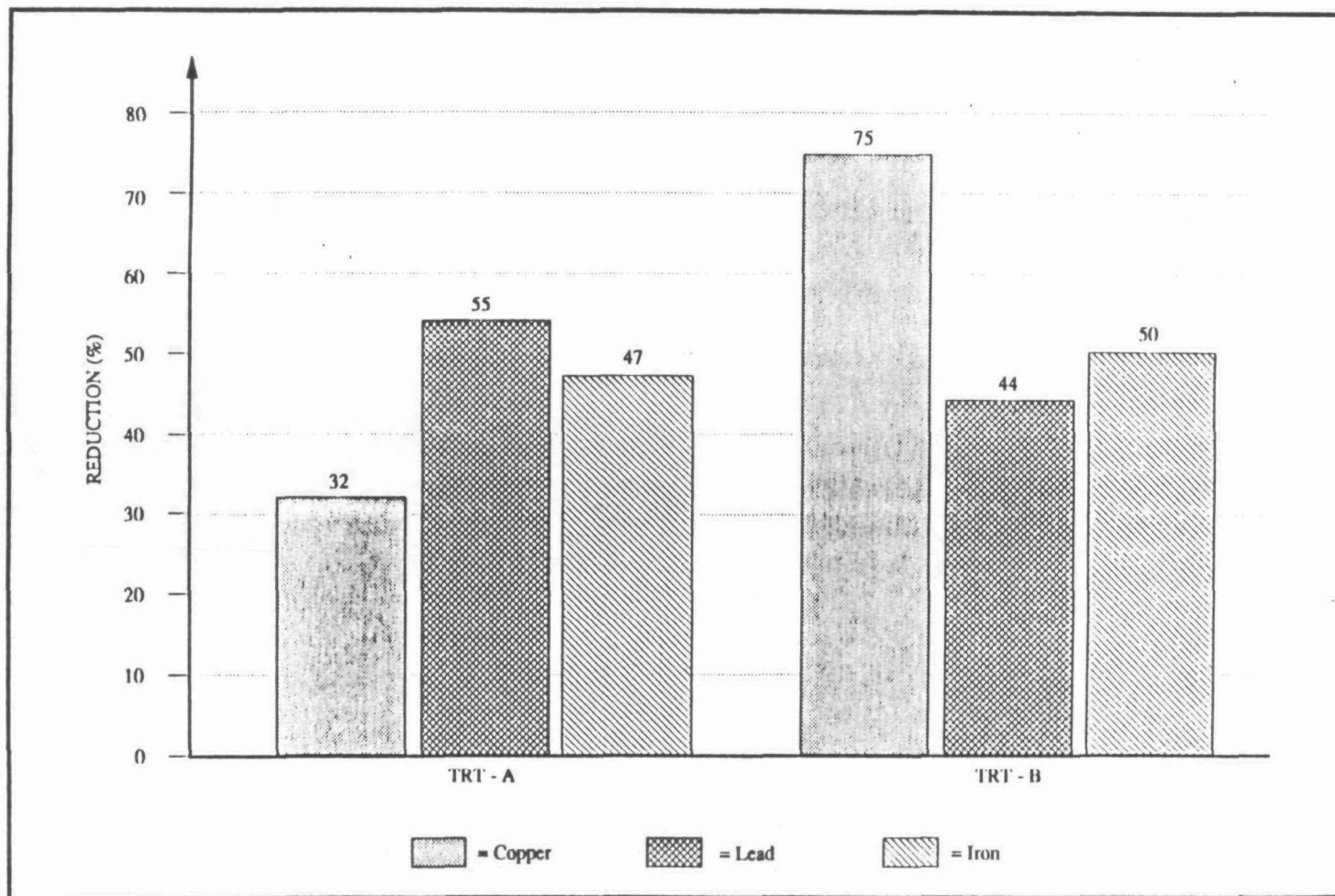


Figure 4-6A. Reduction in Metal Concentrations by Treatment Alternatives

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**Table 4-6. Corrosion Control Treatment Performance Ranking Matrix**

Treatment Alternative	Performance Criteria					
	Metal Solubility			Weight-Loss		
	Copper	Lead	Iron	Copper	Lead	Iron
<b>Weighting Factors</b>	0.40	0.45	0.15	0.40	0.45	0.15
Treatment A	4	7	5.5	7	7	4
Treatment B	7	4	5.5	4	0	7
Existing	0	0	0	0	4	0
<b>Interim Performance Scores</b>						
Treatment A	1.6	3.2	0.8	2.8	3.2	0.6
Treatment B	2.8	1.8	0.8	1.6	0.0	1.1
Existing	0.0	0.0	0.0	0.0	1.8	0.0
<b>Measurement Technique Weighting Factors</b>	0.7	0.7	0.3	0.3	0.3	0.7
<b>Measurement Scores</b>						
Treatment A	1.1	2.2	0.2	0.8	0.9	0.4
Treatment B	2.0	1.3	0.2	0.5	0.0	0.7
Existing	0.0	0.0	0.0	0.0	0.5	0.0
<b>Total Score</b>						
Treatment A	5.8					
Treatment B	4.7					
Existing	0.5					



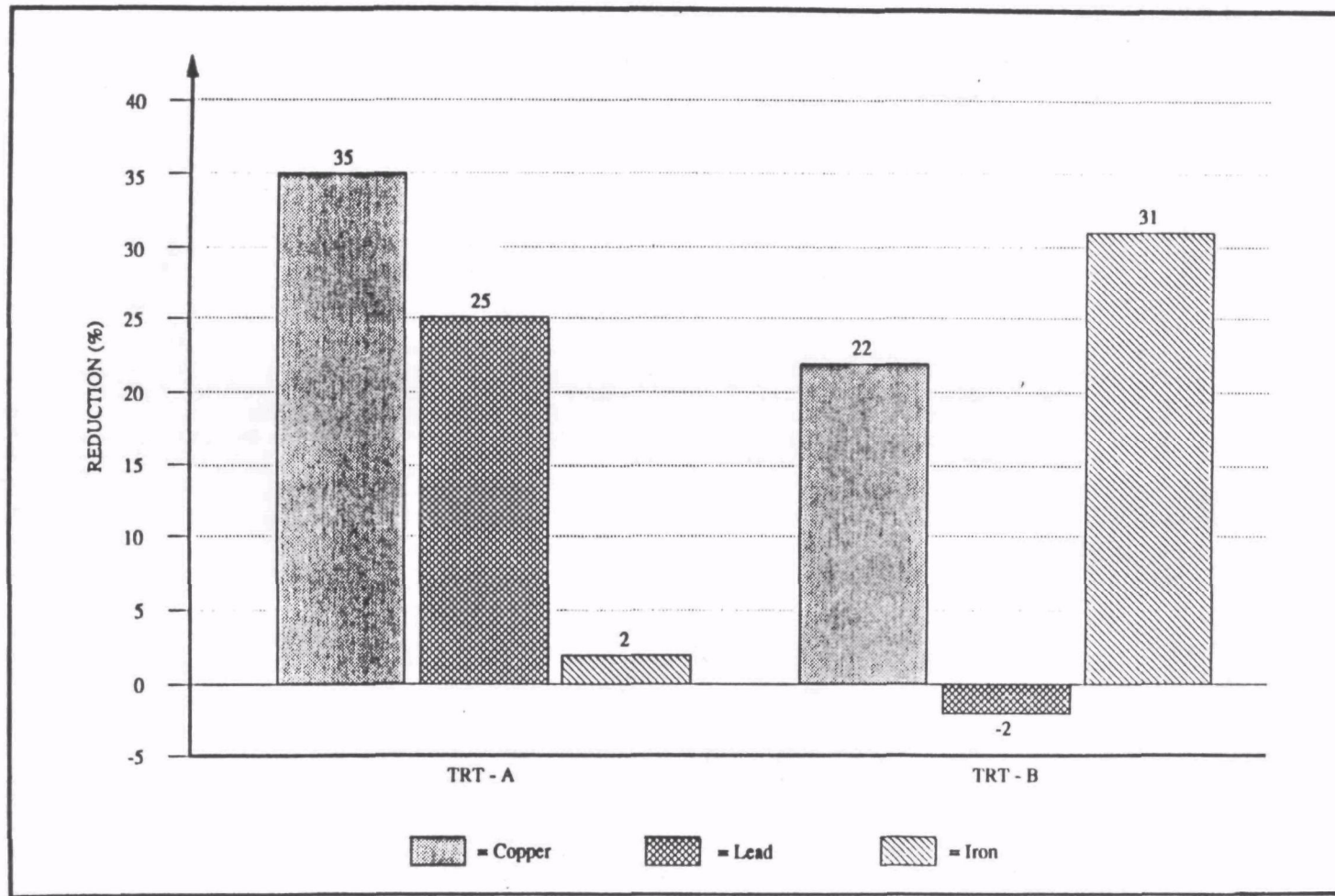


Figure 4-6B. Reduction in Coupon Weight-Loss by Treatment Alternatives



## DEMONSTRATION TESTING

**Table 4-7. Final Corrosion Control Treatment Selection Matrix**

Treatment Alternative	Corrosion Control Performance	Treatment Reliability	Estimated Costs	Total
Weighting Factors	0.75	0.15	0.1	1
Treatment A	7	7	0	6.3
Treatment B	4	0	4	3.4
Existing	0	4	7	1.3

Three identical pipe loops were constructed of copper pipe with lead/tin soldered connections. Loop 1 represented a control loop without treatment, Loop 2 used finished water treated with lime addition, and Loop 3 used finished plant water with the addition of a phosphate inhibitor. The target pH for Loop 2 was 8.3 and the alkalinity and final hardness were allowed to fluctuate to satisfy the final pH goal. Loop 3 water was treated by the addition of a proprietary phosphate inhibitor at a dose calculated to yield 1 mg/L as  $\text{PO}_4$ .

The three loops were run for a period of 35 weeks until they appeared to stabilize and testing was terminated. Water flowed through the loops for 16 hours followed by an 8 hour standing period. Standing water samples were collected for lead analysis once per week for the 35-week period. Data from the tests are given in Table 4-8.

Unless conditioned for an extended period, new piping materials are likely to

yield higher metals concentrations than actual household plumbing systems. Yet, it is extremely difficult to construct pipe loops with materials removed from household plumbing systems without disturbing films and scales present on piping interiors. Results from testing programs, therefore, are used to select treatment techniques; and final action levels after installation of full scale treatment can only be estimated. In the testing program being discussed here, finished water from the treatment facility flowed continuously through all three loops for four weeks in order to partially acclimate the pipe rig before the initiation of the weekly sampling program.

Parametric statistics were selected to compare the two treatments with the control. The data were found to be skewed and were transformed into the log normal mode for analysis. This type of transformation is frequently made when analyzing water quality data and the procedure is

# **DEMONSTRATION TESTING**

**Table 4-8. Lead Concentrations from Pipe Loop Testing**

<b>Week</b>	<b>Loop 1 Pb, mg/L</b>	<b>Loop 2 Pb, mg/L</b>	<b>Loop 3 Pb, mg/L</b>
1	0.062	0.130	0.078
2	0.078	0.100	0.102
3	0.125	0.080	0.115
4	0.110	0.095	0.109
5	0.175	0.110	0.126
6	0.205	0.135	0.102
7	0.190	0.108	0.098
8	0.162	0.092	0.075
9	0.078	0.079	0.082
10	0.112	0.085	0.070
11	0.095	0.090	0.068
12	0.132	0.076	0.065
13	0.126	0.079	0.081
14	0.103	0.108	0.073
15	0.115	0.087	0.065
16	0.138	0.072	0.068
17	0.092	0.068	0.072
18	0.100	0.052	0.038
19	0.118	0.097	0.055
20	0.107	0.075	0.062
21	0.068	0.048	0.050
22	0.082	0.072	0.068
23	0.097	0.103	0.076
24	0.112	0.096	0.072
25	0.085	0.072	0.075
26	0.078	0.080	0.080
27	0.060	0.052	0.062
28	0.092	0.058	0.054
29	0.075	0.045	0.058
30	0.087	0.053	0.045
31	0.063	0.060	0.052
32	0.072	0.055	0.068
33	0.068	0.052	0.030
34	0.080	0.048	0.051
35	0.091	0.057	0.042

## DEMONSTRATION TESTING

explained more fully in Appendix C for this example. The Student's *t* statistic was used to compare paired data among the three loops and the results from these analyses are reproduced in Table 4-9 from Appendix C.

Using the entire data set for 35 weeks, the data in Table 4-9 seem to indicate that either treatment would be beneficial for reducing lead concentrations. However, after reviewing the data, it was noted that the data had fewer fluctuations during the later weeks. These results are reasonable as the pipes become more acclimated and the system stabilizes as the testing program proceeds. Using a data set from week 25 on, the data were examined once again. This analysis showed that each treatment was significantly different when compared to the control, but there was no apparent statistical difference between treatments. Thus, Utility A will examine other factors such as initial cost, operating costs, and operating philosophy before deciding which treatment to implement for full-scale treatment.

### 4.9.2 Static Testing.

The City of Starboard, a large PWS, has a surface water supply with low pH, alkalinity and hardness levels as shown in Table 4-10. Based on the desk-top evaluation, the optimal corrosion control treatment recommended for further evaluation was pH/alkalinity adjustment. The use of inhibitors was eliminated on the basis of the desk-top evaluation. The water quality goals selected on the basis of lead and copper passivation were: pH 7.6 - 7.8; total alkalinity = 40 - 45 mg/L CaCO<sub>3</sub>; and total hardness ≥ 30 mg/L CaCO<sub>3</sub>.

Three treatment alternatives were selected for demonstration testing using static tests: (1) lime and carbon dioxide; (2) soda ash and carbon dioxide; and (3) lime and sodium bicarbonate. The average chemical feed rates and water quality characteristics for testing are presented in Table 4-11.

The demonstration tests used to evaluate corrosion control performance consisted of immersion tests with flat

**Table 4-9. Calculated Student's *t* Values**

Comparison	<i>t</i>
Loop 1 and Loop 2	5.46***
Loop 1 and Loop 3	6.98***
Loop 2 and Loop 3	2.87**
<b>Notes:</b> All test data transformed to logarithmic values ** Highly significant difference at the 0.01 level *** Extremely significant difference at the 0.001 level	

## DEMONSTRATION TESTING

**Table 4-10. Average Raw, Treated, and Finished Water Quality for the Static Demonstration Tests by the City of Starboard**

Water Quality Parameter	Raw Water	Treated Water	Finished Water
pH	7.2	6.7	7.4
Alkalinity, mg/L $\text{CaCO}_3$	24	10	16
Calcium Hardness, mg/L $\text{CaCO}_3$	18	16	20
Chlorine Residual, mg/L	N/A	0.4	1.2

**Table 4-11. Average Chemical Feed Rates and Water Quality Characteristics by Treatment Alternative for the Static Demonstration Testing Program by the City of Starboard**

Treatment Alternative	Water Quality Characteristics, mg/L			Chemical Feed Rates, mg/L			
	THd	Talk	pH	CaO	$\text{Na}_2\text{CO}_3$	$\text{NaHCO}_3$	$\text{CO}_2$
CaO/ $\text{CO}_2$	42	32	8.0	17.4	0	0	15.3
$\text{Na}_2\text{CO}_3/\text{CO}_2$	22	27	8.0	0	16.8	0	7.8
$\text{NaHCO}_3/\text{CaO}$	22	29	8.0	1.4	0	31.5	0

## DEMONSTRATION TESTING

metal coupons of iron, lead, and copper. Figure 4-7 illustrates the experimental set up for the immersion tests. The testing program was conducted by suspending four metal coupons in each of three test jars and the one control jar for each metal included in the investigation. The solutions were maintained for one-week testing periods, then sampled, drained, and replaced with fresh solutions. Water quality parameters were measured daily in each jar to ensure their relative consistency throughout the testing period. The pH was adjusted with carbon dioxide or sodium hydroxide, as needed. Alkalinity and hardness contents remained very stable during the week holding period, and did not require adjustment.

The testing schedule, as presented in Figure 4-8, included: iron coupon testing for 4.5 months; lead coupons for 7 months; and copper coupons for 13 months in order to achieve stable conditions by the end of the testing period. Metal leaching data were collected by sampling the test and control solutions prior to draining the jars at the conclusion of each week. The control and test jars were all treated the same in terms of the monitoring frequency. This ensured the integrity of the relative metal leaching data between control and test conditions.

Table 4-12 presents the raw data generated during the testing program in terms of water quality parameter monitoring and metal leaching. A sample log sheet for the testing program is presented in

Figure 4-9 to illustrate the data recording and documentation requirements.

Figures 4-10A and 4-10B present the metal leaching results for copper and lead in terms of the reduction in total metal between the test and control jars. A high degree of variability is evident from the copper results, while more consistent data was found for lead. The lime and carbon dioxide treatment provided the greatest reduction in copper levels consistently throughout the testing period. The difference in the performance between the other two treatments for copper control is minimal, and, throughout the majority of the testing period, both indicated increased copper corrosion over the existing conditions (i.e., negative reductions as presented in Figure 4-10A).

Each of the three alternative treatments provided positive reductions in lead corrosion as shown in Figure 4-10B. Large variability was observed in the performance of soda ash plus carbon dioxide while lime plus carbon dioxide and sodium bicarbonate plus carbon dioxide provided very consistent results. The lime and carbon dioxide treatment, however, resulted in lower lead levels with respect to the control throughout the entire evaluation period.

Based on these results, the lime and carbon dioxide treatment was selected as optimal treatment since it provided the greatest and most consistent reduction in corrosion for lead and copper.

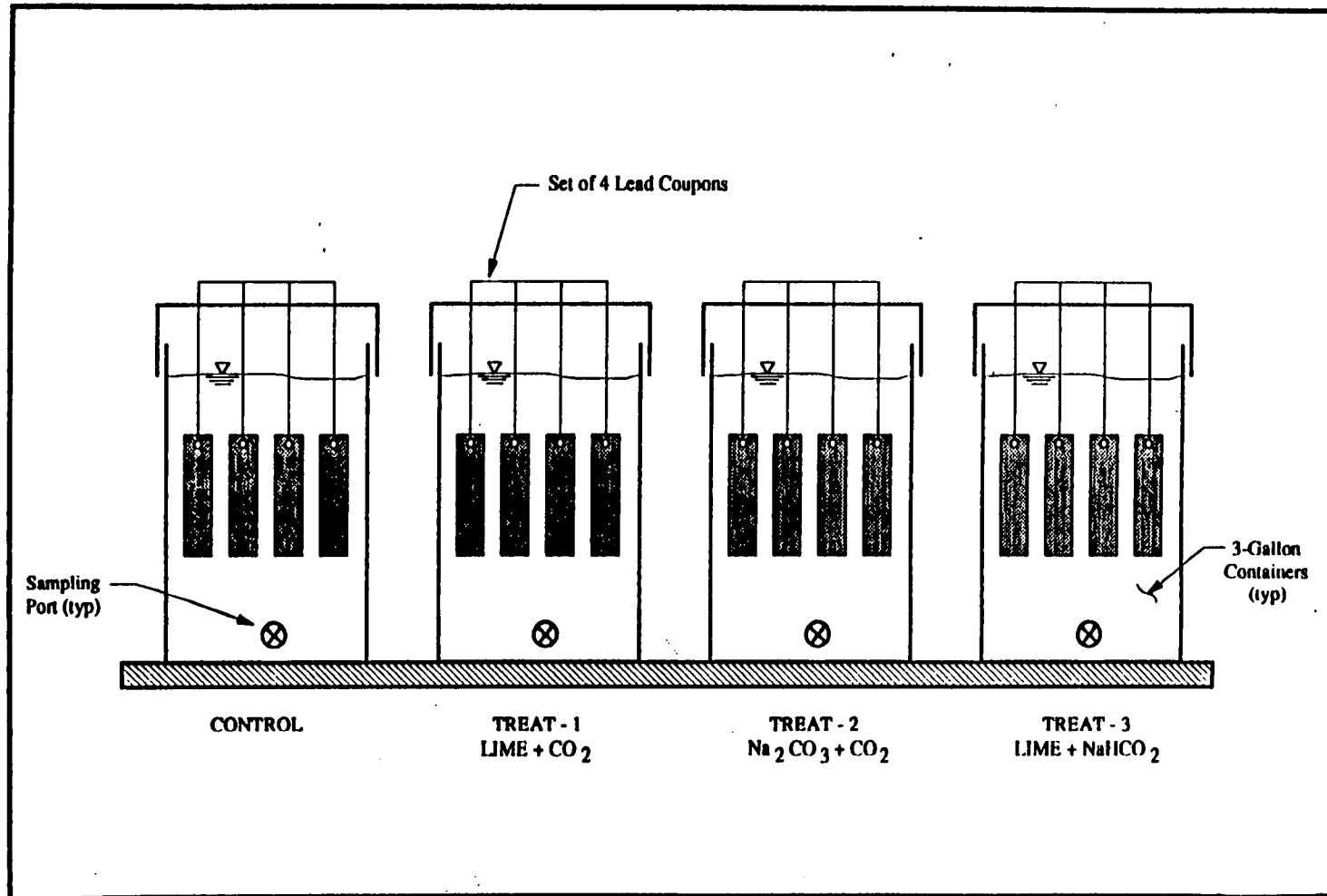
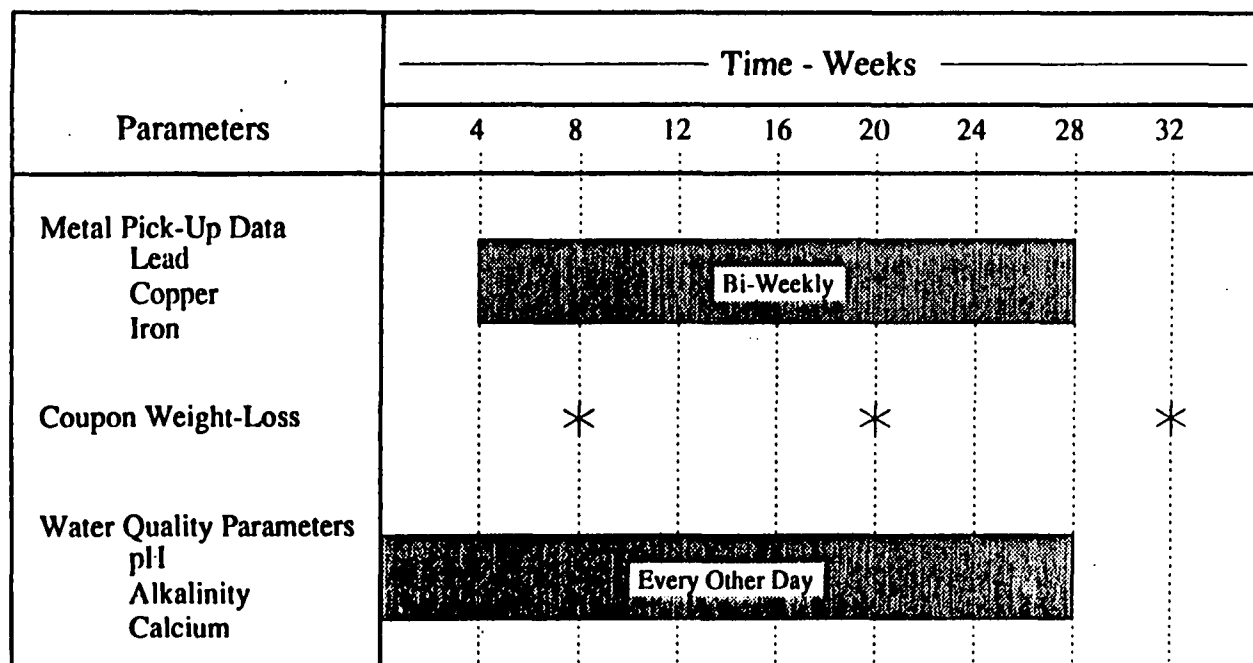


Figure 4-7. Immersion Testing Set-Up



**Figure 4-8. Testing Program for City of Starboard Static Demonstration Tests**

**Table 4-12. Testing Program Raw Data for Water Quality Parameters<sup>3</sup> and Metal Leaching<sup>4</sup> Measurements for the Static Demonstration Tests by the City of Starboard**

Test Week	Alternative Treatment	Initial Conditions, mg/L					Final Conditions, mg/L				
		pH <sup>1</sup>	Alk <sup>2</sup>	Ca <sup>2</sup>	Cu	Pb	pH <sup>1</sup>	Alk <sup>2</sup>	Ca <sup>2</sup>	Cu	Pb
2	Lime + CO <sub>2</sub>	6.48	5	9	ND	ND	7.88	32	44	0.248	0.124
4	Lime + CO <sub>2</sub>	6.52	6	8	ND	ND	7.98	33	42	0.254	0.135
6	Lime + CO <sub>2</sub>	6.22	5	9	ND	ND	8.25	35	43	0.361	0.122
8	Lime + CO <sub>2</sub>	6.38	5	7	ND	ND	8.12	37	44	0.182	0.146
10	Lime + CO <sub>2</sub>	6.51	4	12	ND	ND	8.05	30	50	0.268	0.138
12	Lime + CO <sub>2</sub>	6.47	4	10	ND	ND	8.16	28	48	0.177	0.166
14	Lime + CO <sub>2</sub>	6.44	6	15	ND	ND	8.23	34	48	0.198	0.153
16	Lime + CO <sub>2</sub>	6.52	5	9	ND	ND	7.92	27	42	0.241	0.142
18	Lime + CO <sub>2</sub>	6.66	4	8	ND	ND	7.78	29	37	0.220	0.121
20	Lime + CO <sub>2</sub>	6.56	4	9	ND	ND	8.16	30	40	0.154	0.118
22	Lime + CO <sub>2</sub>	6.31	5	9	ND	ND	8.08	34	42	0.146	0.092
24	Lime + CO <sub>2</sub>	6.43	6	7	ND	ND	8.01	32	44	0.132	0.062
26	Lime + CO <sub>2</sub>	6.54	4	6	ND	ND	8.11	30	38	0.148	0.056
28	Lime + CO <sub>2</sub>	6.63	5	8	ND	ND	8.04	35	39	0.162	0.078
30	Lime + CO <sub>2</sub>	6.48	5	8	ND	ND	7.94	29	40	0.127	0.063

<sup>1</sup> The measurement units are standard pH units.

<sup>2</sup> Alkalinity and Calcium measurements are in mg/L CaCO<sub>3</sub>.

<sup>3</sup> Water Quality Parameter results are the average of measurements taken every other day within the two week test period.

<sup>4</sup> Metal results are the average of three aliquots taken at each sampling event.



## DEMONSTRATION TESTING

**Figure 4-9. Immersion Testing Data Recording and Documentation Sheets**

<b>Date:</b>	
<b>Time:</b>	
<b>Analyst:</b>	
<b>Test Week:</b>	
<b>Test Day:</b>	

Water Quality Parameters								
Treatment	Water Quality Parameters							
	pH		T		Alk		Ca	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Control								
Trt Alt 1								
Trt Alt 2								
Trt Alt 3								

Metal Leaching Analysis							
Immersion Testing							
Treatment	Metal Content in mg/L						
	Lead		Copper		Iron		
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	
Control							
Trt Alt 1							
Trt Alt 2							
Trt Alt 3							

QA/QC Testing Results:						
Treatment	Lead		Copper		Iron	
	Blank	Spike	Blank	Spike	Blank	Spike
Control						
Trt Alt 1						
Trt Alt 2						
Trt Alt 3						

Weight-Loss Measurements, mpy						
Treatment	Lead		Copper		Iron	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Control						
Trt Alt 1						
Trt Alt 2						
Trt Alt 3						

## DEMONSTRATION TESTING

**Figure 4-9. Immersion Testing Data Recording and Documentation Sheets (continued)**

**Date:**

**Time:**

**Analyst:**

**Test Week:**

**Test Day:**


### NOTES:

Visual Inspection of Coupons:

Testing/Analytical Procedures:

QA/QC Program:

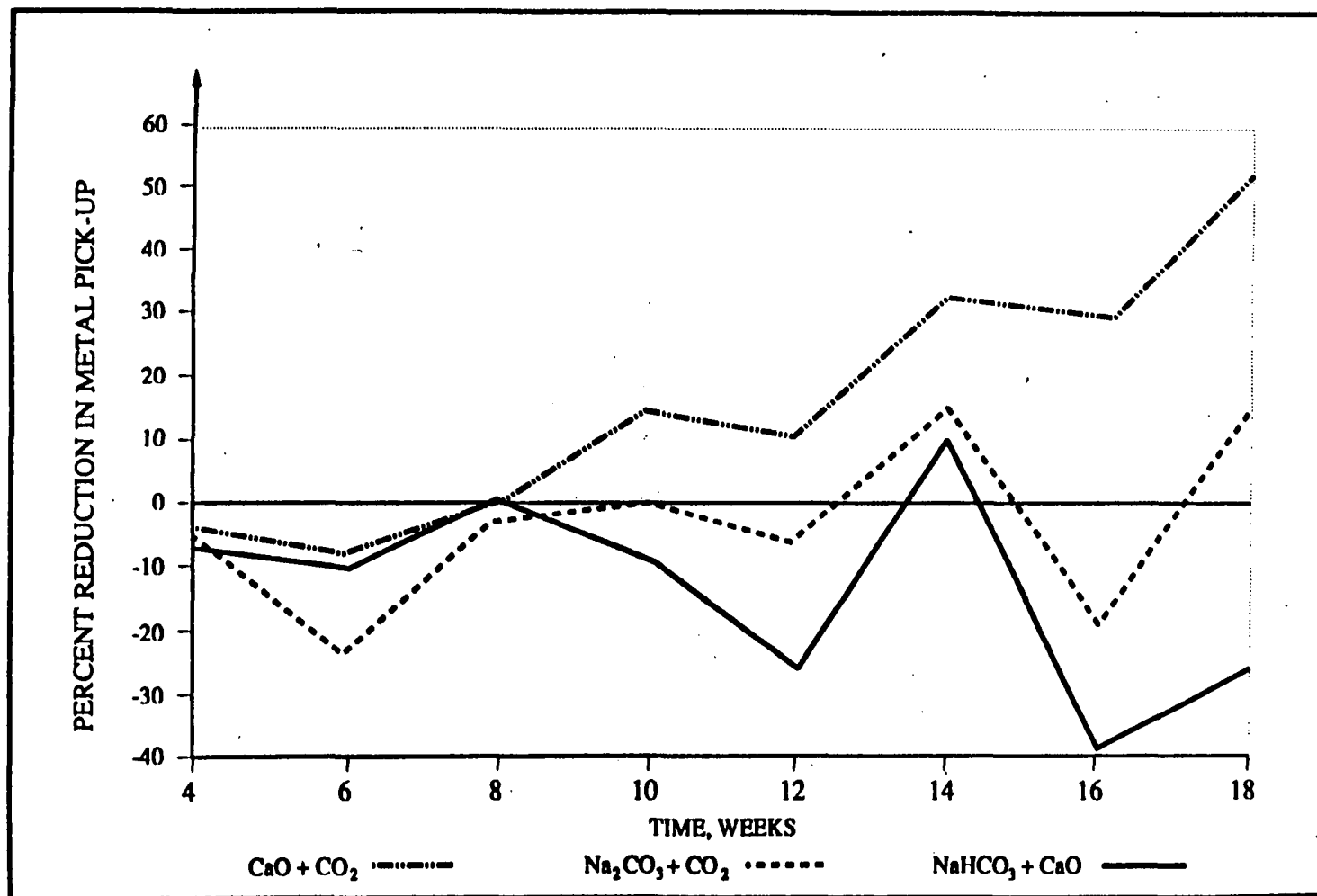


FIGURE 4-10A. Reductions in Copper Corrosion for Treatment Alternatives

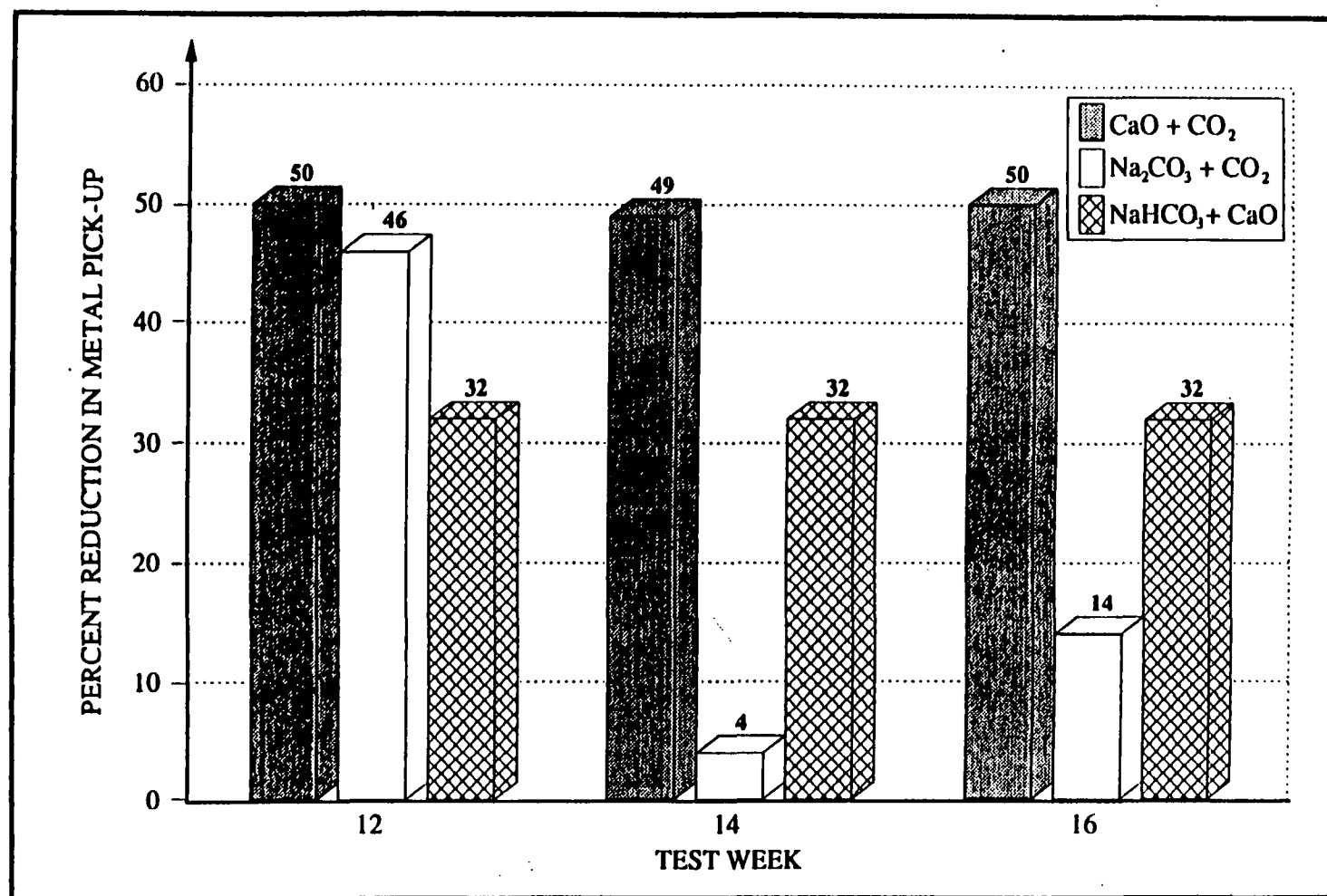


Figure 4-10B. Reductions in Lead Corrosion for Treatment Alternatives

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## Chapter 5.0 — **Full-Scale Operation and Implementation of Optimal Corrosion Control Treatment**

The purpose of this chapter is to provide guidance on several aspects of full-scale implementation of corrosion control treatment, including the following steps which PWSs and States may encounter:

- Developing the operating ranges for optimal treatment after follow-up monitoring has been completed.
- Diagnosing problems associated with the startup of full-scale treatment.
- Identifying the need to modify the installed treatment to improve corrosion control protection.
- Implementing changes in treatment which may improve the overall performance of corrosion control treatment.

### **5.1 Overview of Requirements**

#### **5.1.1 Installing Optimal Treatment.**

The Rule requires that once treatment is installed, follow-up monitoring must be performed by PWSs. At the conclusion of this monitoring effort, States will review the results and establish operational conditions which must be met during all routine monitoring events for all large PWSs and those small and medium-size PWSs that exceed an AL in the follow-up monitoring. The operating conditions will consist of minimum, maximum, or ranges

of water quality parameter values which must be achieved in the potable water entering and residing in the distribution system at all times. Additionally, PWSs will be required to at least report the chemical dosages applied during the reporting period.

States will be facing the challenges of: (1) determining whether the recommended treatments provided by PWSs are acceptable, or whether additional action on their part is required; (2) establishing operating conditions which adequately define optimal treatment for each PWS; and (3) determining compliance for each PWS on the basis of continual achievement of the site-specific operating conditions.

PWSs, on the other hand, will be facing challenges regarding the identification and execution of optimizing corrosion control treatment. Many factors act on distribution and home plumbing systems beyond treated water quality to cause corrosion activity increases and decreases. It will be difficult for many PWSs to properly assess the ability of treatment changes to optimize or improve the corrosion control protection afforded due to the complex nature of corrosion activity and the variety of materials targeted for protection.

A two-year installation and startup period follows State designation of optimal corrosion control treatment. Systems

## OPERATION AND IMPLEMENTATION

should conduct additional sampling and monitoring during this period in order to optimize their operations prior to conducting the required follow-up monitoring. Information needs to be gathered regarding changes in the active chemical forms used for corrosion control regardless of whether precipitation or passivation techniques are employed. For example, if a polyphosphate inhibitor is added to the treated water, it is important to know the concentrations of both orthophosphate and polyphosphate within the distribution system. Important water quality parameters should be measured at the entry points to the distribution system and at various locations within the system including the extremities. Some of the locations monitored during the initial monitoring period should be included.

The primary goal of corrosion control optimization is to achieve and maintain compliance with the lead and copper ALs. However, optimized treatment may exist even though the ALs are exceeded. Further, corrosion control treatment programs must be coordinated with the requirement that all other drinking water standards be met. As noted previously, variations in pH, calcium, and alkalinity that may have positive impacts on compliance with the lead and copper ALs may be detrimental to meeting other criteria. These interrelationships are site-specific and must be defined in each corrosion study. Additionally, optimization may include economic factors so that the most cost-effective means of implementing optimal corrosion control treatment may be achieved.

After corrosion control facilities are operational, optimization should be viewed

as a dynamic, rather than static process, where ongoing efforts are made to minimize lead and copper concentrations over time. In addition, future follow-up monitoring, even at reduced frequencies, will require PWSs to formally review the effectiveness of their programs on a periodic basis. As such, corrosion control is an essential and permanent component of an overall water treatment program and PWSs should audit their programs on a routine basis.

### ***5.1.2 Schedule.***

Optimal corrosion control treatment, if required, must be installed and operational by the dates presented in Table 5-1. Large systems will have 30 months from the time the corrosion control study is complete until the optimal facilities are on line. This includes a six-month period for the State to review the study and approve the optimal corrosion control approach. Small and medium systems will be required to submit recommendations for optimal corrosion control treatment to the State within six months of exceeding an AL. The State may then take one of the following actions:

- Approve the recommended treatment approach.
- Disapprove or modify the recommended treatment approach.
- Require the installation of an alternate treatment approach.
- Require the purveyor to prepare a study that identifies the optimal corrosion control approach for that system.

Should a small or medium PWS be required to conduct a corrosion control

**Table 5-1. Key Compliance Dates for Large, Medium, and Small Systems**

<b>System Designation</b>	<b>System Population</b>	<b>Initiate Tap Sampling Program</b>	<b>Complete Tap Sampling Program</b>	<b>Complete Corrosion Control Study</b>	<b>Complete Installation of Optimal Facilities</b>
Large	>50,000	01/92	01/93	07/94	01/97
Medium	> 3,300 & ≤ 50,000	07/92	01/93*	07/95	01/98
Medium (State Designates Treatment)	> 3,300 & ≤ 50,000	07/92	01/93*	N/A	07/96
Small	≤ 3,300	07/93	01/94*	07/96	01/99
Small (State Designates Treatment)	≤ 3,300	07/93	01/94*	N/A	01/98

\* The deadlines for those small and medium-size PWSs that meet the ALs in the first six-month round of initial monitoring and fail in the second six-month monitoring period would be delayed by six months.



study by the State, then 18 months are provided for performing the study and an additional 30 months until treatment must be installed and on line.

## 5.2 Full-Scale Operation of Treatment Alternatives

The development of reasonable operating criteria by which optimal treatment may be described is a compliance step which PWSs and States will be required to implement. At the completion of follow-up monitoring, States are expected to establish the operating ranges or conditions by which PWSs will be judged to be operating optimal corrosion control treatment. These conditions establish the compliance requirements for large PWSs and those small and medium-size PWSs that exceed an AL in the follow-up monitoring. Therefore, it is extremely important that a balance be achieved between: (1) accurately defining optimal treatment goals, and, (2) realistically setting conditions which are feasible to be met by full-scale treatment facilities *AT ALL TIMES*.

### 5.2.1 Startup Operations.

The transition between bench scale or pipe loop studies and full scale operation is a major one and some difficulties are to be anticipated. The purchase, installation, and trouble-shooting of new equipment are considered to be a normal part of operating a treatment facility and are not discussed here. These functions are extremely necessary, however, and should be performed accordingly.

Startup procedures will vary from facility to facility depending upon the

chemicals fed, whether chemicals are dry or liquid, and the type of metering equipment used. In general, more attention needs to be given the entire system during the startup period to ascertain that the proper results are being achieved. Cumulative feed rates for chemicals should initially be recorded at least once per hour and never should be recorded less than once each shift. Metering equipment should be checked for initial accuracy and occasionally thereafter. Some new equipment has a tendency to "drift" at first and it may take a few weeks of operation before the feed rate is consistent. Routine process control and monitoring the product in the treated water are essential elements of any startup program.

Unfortunately many chemicals can be expressed in different units and this can lead to confusion for the unsuspecting operator. The operator needs to determine the amount of active ingredient that is to be fed for corrosion control and then monitor for that ingredient. For instance, the results of a corrosion control study may have determined that a certain inhibitor should be fed at a dose rate of approximately 0.2 mg/L as phosphorus, P, while the supplier identifies his product in terms of phosphate,  $\text{PO}_4$ . Calcium is sometimes expressed as calcium (Ca), or as lime ( $\text{CaO}$ ), or as hydrated lime [ $\text{Ca}(\text{OH})_2$ ], or as calcium carbonate [ $\text{CaCO}_3$ ]. The following information may help to avoid confusion.

- 1 mg/L Ca = 1.40 mg/L Ca as CaO  
                   = 1.85 mg/L Ca as  $\text{Ca}(\text{OH})_2$   
                   = 2.50 mg/L Ca as  $\text{CaCO}_3$
- 1 mg/L P = 3.1 mg/L P as  $\text{PO}_4$

Although the startup of chemical feed systems for pH, alkalinity, and calcium

adjustment may require more in-plant attention to regulate dose rates and final adjusted water quality; the addition of an inhibitor is likely to cause more customer concerns. It is not unusual for inhibitors to loosen existing corrosion byproducts when introduced into a distribution system for the first time. These corrosion materials can then be transported to the user's tap and water quality complaints regarding red water, dirty water, sediment, color, or taste and odor may result. Initial doses may be substantially higher than the recommended maintenance dose (three to ten times) in order to acclimate the distribution system to the inhibitor. Alternatively, some systems may need to gradually increase the initial dosages to the maintenance level to minimize the adverse effects that may result from loosening existing corrosion scale or byproducts in the distribution system. These doses may be necessary from a few days to several months in order to accomplish the objectives of the corrosion control program. Additionally, a flushing program during this time can assist in removing corrosion byproducts from dead end locations within the distribution system and also in ensuring that the inhibitor moves throughout the entire system. Because most inhibitors are proprietary products with unknown formulations, it can be difficult to chemically monitor the residual of the inhibitor in the system. Therefore, physical inspections along with maintaining customer comment logs are recommended. It is important to work closely with a reputable supplier to minimize customer complaints while installing full-scale corrosion control treatment.

### **5.2.2 Operating Ranges.**

This section will discuss some of the factors that impact an operator's ability to control chemical feed rates and the concentration of calcium, carbonate, and corrosion inhibitors within the distribution system.

#### **5.2.2.1 Historic operating ranges.**

Technically, pH is an exponential function of the hydrogen ion concentration and calculating the mean hydrogen ion concentration is the appropriate procedure for determining average pH levels. Practically, however, the finished water pH is normally stable enough to allow the arithmetic mean to be used without introducing significant error into operating guidelines. Table 5-2 presents a statistical summary of pH and alkalinity data taken from a variety of water treatment plants across the country. This table shows the annual average (mean) values and the operating range in which 90 percent of the daily values fell. The table also indicates how far the 90 percent range varied from the mean.

A key finding of this work is that site-specific water quality considerations influence the operating ranges that can be achieved. For example, the 90 percent operating range for pH varied from the mean by  $\pm 0.2$  units at several sites to  $\pm 1.0$  units at another. For alkalinity, the variance from the mean was about  $\pm 10$  mg/L  $\text{CaCO}_3$  for alkalinities below 50 mg/L  $\text{CaCO}_3$ ;  $\pm 20$  mg/L  $\text{CaCO}_3$  for alkalinities between 50 to 100 mg/L  $\text{CaCO}_3$ ; and  $\pm 30$  mg/L  $\text{CaCO}_3$  for alkalinities over 100 mg/L  $\text{CaCO}_3$ .

The type of chemical used to adjust pH may also influence daily variations from the mean. Figure 5-1A shows the pH

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**Table 5-2. Operating Ranges for pH and Alkalinity for  
10 Water Treatment Plants**

Facility	pH (units)			Alkalinity (mg/l as CaCO <sub>3</sub> )		
	Annual Average	90% Range	Variance	Annual Average	90% Range	Variance
Plant A (Texas)	8.6	8.2-9.0	±0.4	36	26-46	±10
Plant B (Texas)	8.4	8.0-8.8	±0.4	29	19-39	±10
Plant C (Illinois)	9.0	8.6-9.4	±0.4	58	30-86	±28
Plant D (North Carolina)	8.0	7.4-8.6	±0.6	29	23-35	±6
Plant E (North Carolina)	7.2	6.8-7.6	±0.4	25	19-31	±6
Plant F (Minnesota)	7.1	6.9-7.3	±0.2	74	56-92	±18
Plant G (Georgia)	7.1	6.1-8.1	±1.0	N/A	N/A	N/A
Plant H (North Carolina)	7.6	7.4-7.8	±0.2	31	23-39	±8
Plant I (Missouri)	7.8	7.6-8.0	±0.2	132	102-162	±30
Plant J (Colorado)	7.5	6.9-8.1	±0.6	37	29-45	±8

frequency distribution for Plant D, where moderate amounts of hydrated lime, 10 to 40 mg/L as  $\text{Ca}(\text{OH})_2$ , are added to neutralize the acidity of the raw water. As shown, the finished pH can vary substantially. In this example, 90 percent of the average daily pH values were within 0.6 units of the mean. In contrast, Figure 5-1B shows the pH frequency distribution for Plant H treating the same type of water using sodium hydroxide. At this location, 90 percent of the values were within 0.2 units of the mean, a tighter range.

In this comparison, sodium hydroxide seemed to provide for tighter pH control. This is not always the case, however. For instance, if the raw water did not have sufficient alkalinity and buffering capacity, the use of sodium hydroxide can result in the same or wider pH variations than for lime. It is also of interest that for both plants noted in this example, a phosphate corrosion inhibitor is used and the pH variations are not a major concern with respect to corrosion control. For those systems, one of the parameters that must be monitored is the active chemical agent within the inhibitor, i.e., orthophosphate or silica. It is not appropriate, for example, to monitor zinc levels when using a zinc orthophosphate inhibitor and presume the orthophosphate concentrations correspond directly.

Figures 5-2A and 5-2B show the finished phosphate content of the water prior to entry into the distribution system. These data indicate that the daily residual may vary from 0.2 to 0.5 mg-P/L from the long-term average. The distribution system residual will, of course, experience even greater variations. Because some of the active chemical ingredient in an inhibitor

will be consumed or deposited within the system, the inhibitor dose will need to be larger than the minimum level which should be maintained throughout the distribution system.

States should consider the average, minimum and maximum values for such water quality parameters based on several years of operating data, if possible, in determining the minimum or range to be established for the water quality parameters. Variations in water quality conditions entering the distribution system will affect the effectiveness of corrosion control treatment. Calcium carbonate can be somewhat resistant to interruptions in effective treatment once the deposits have hardened. However, the protection provided by carbonate passivation and inhibitor systems is more vulnerable to disruptions in treatment or water quality variability (Elmund, 1992; Lechner, 1991). In these cases, minimum values rather than average distribution system conditions are preferable for pH, alkalinity, orthophosphate or silica (whichever parameters apply).

**5.2.2.2 Recommended operating ranges.** Based on the above discussion, site-specific conditions contribute to the achievable operating ranges for finished water quality parameters at each facility. States are required by the Rule to set operating conditions which best describe the "optimal" corrosion control treatment installed at each facility. Additionally, the Rule requires that the results from water quality parameter monitoring at distribution system points of entry—minimally required to be performed every two weeks—and at representative locations

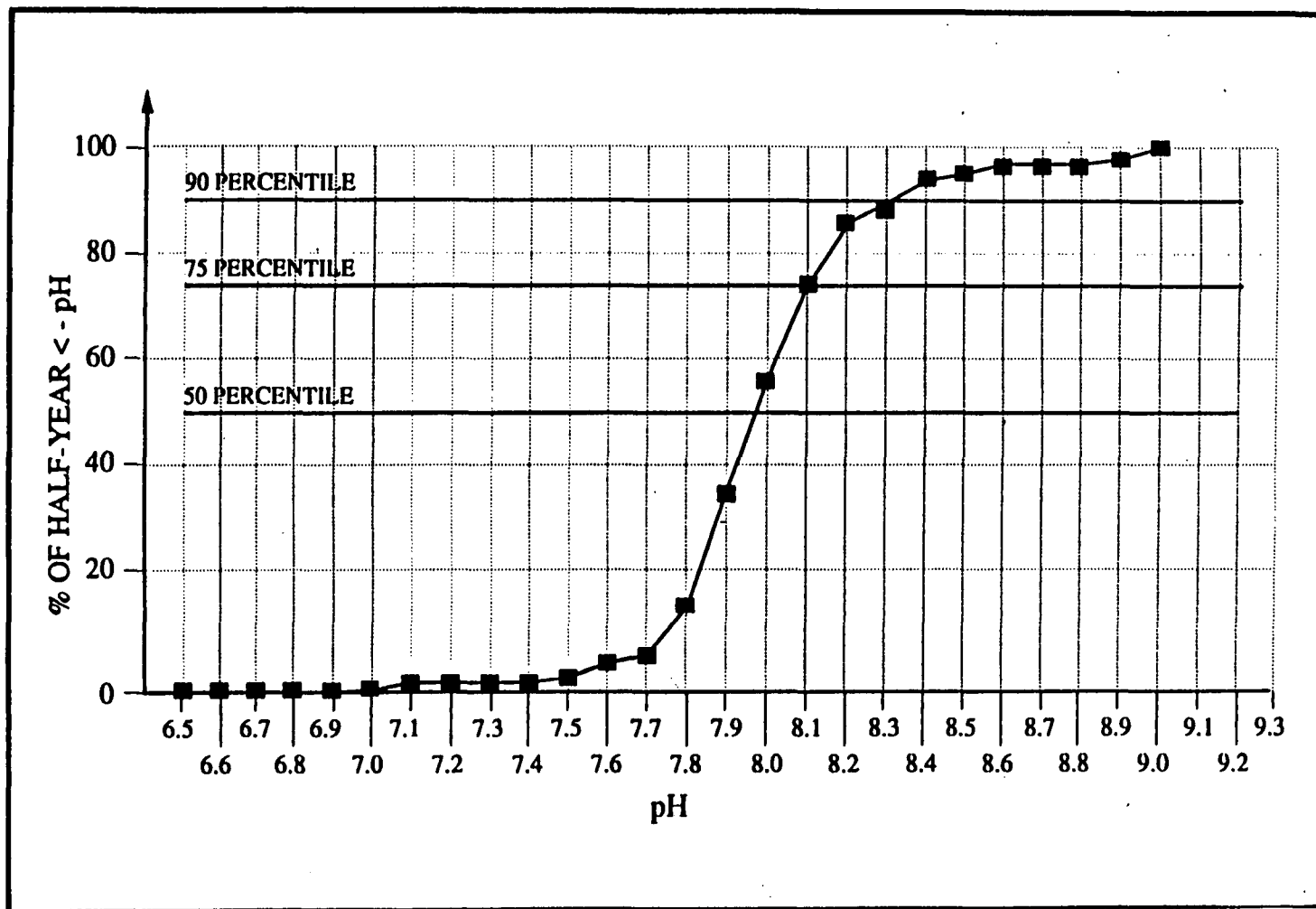
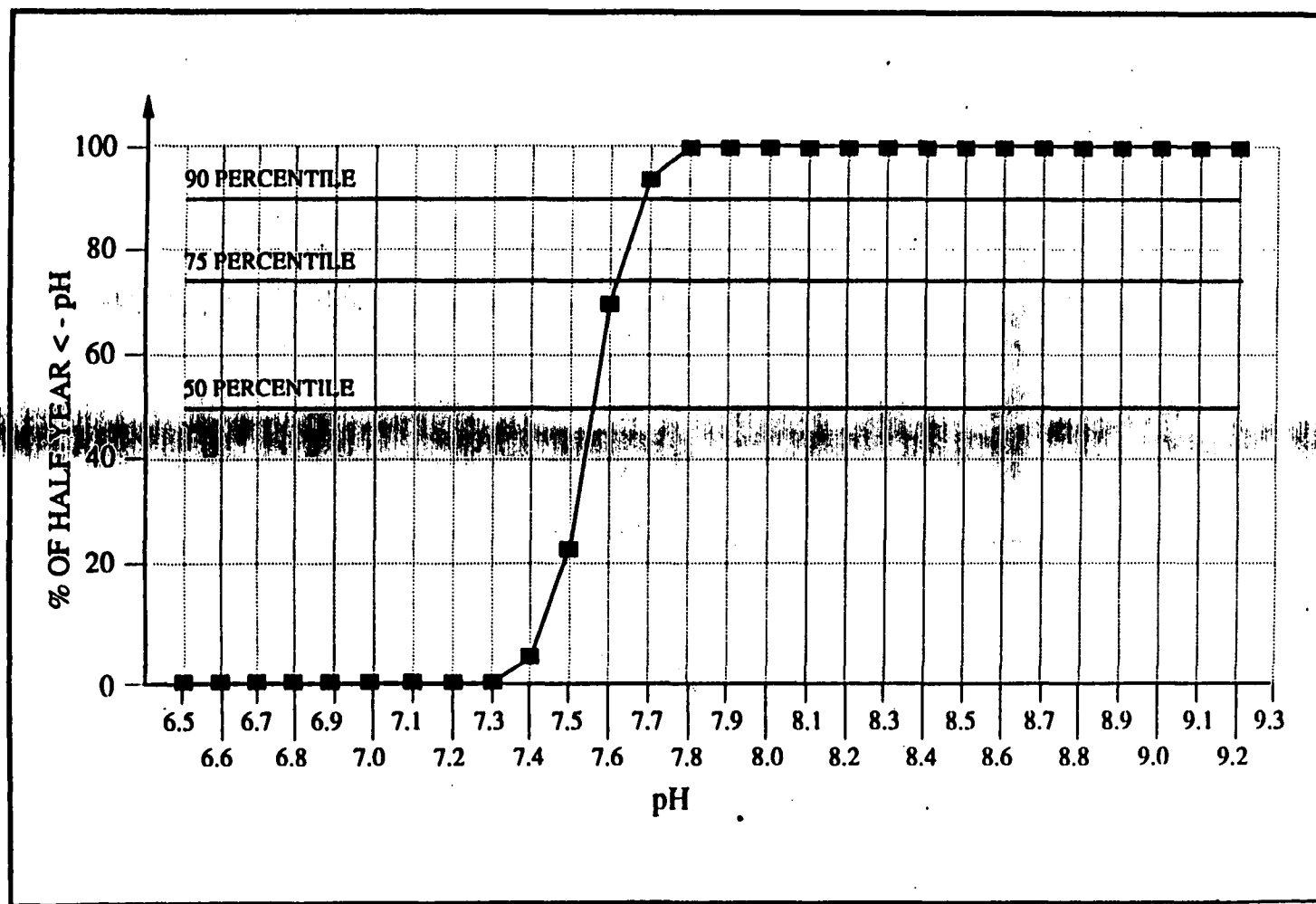


Figure 5-1A. pH Cumulative Frequency Distribution, January to June  
Plant D



**Figure 5-1B. pH Cumulative Frequency Distribution, January to June  
Plant H**

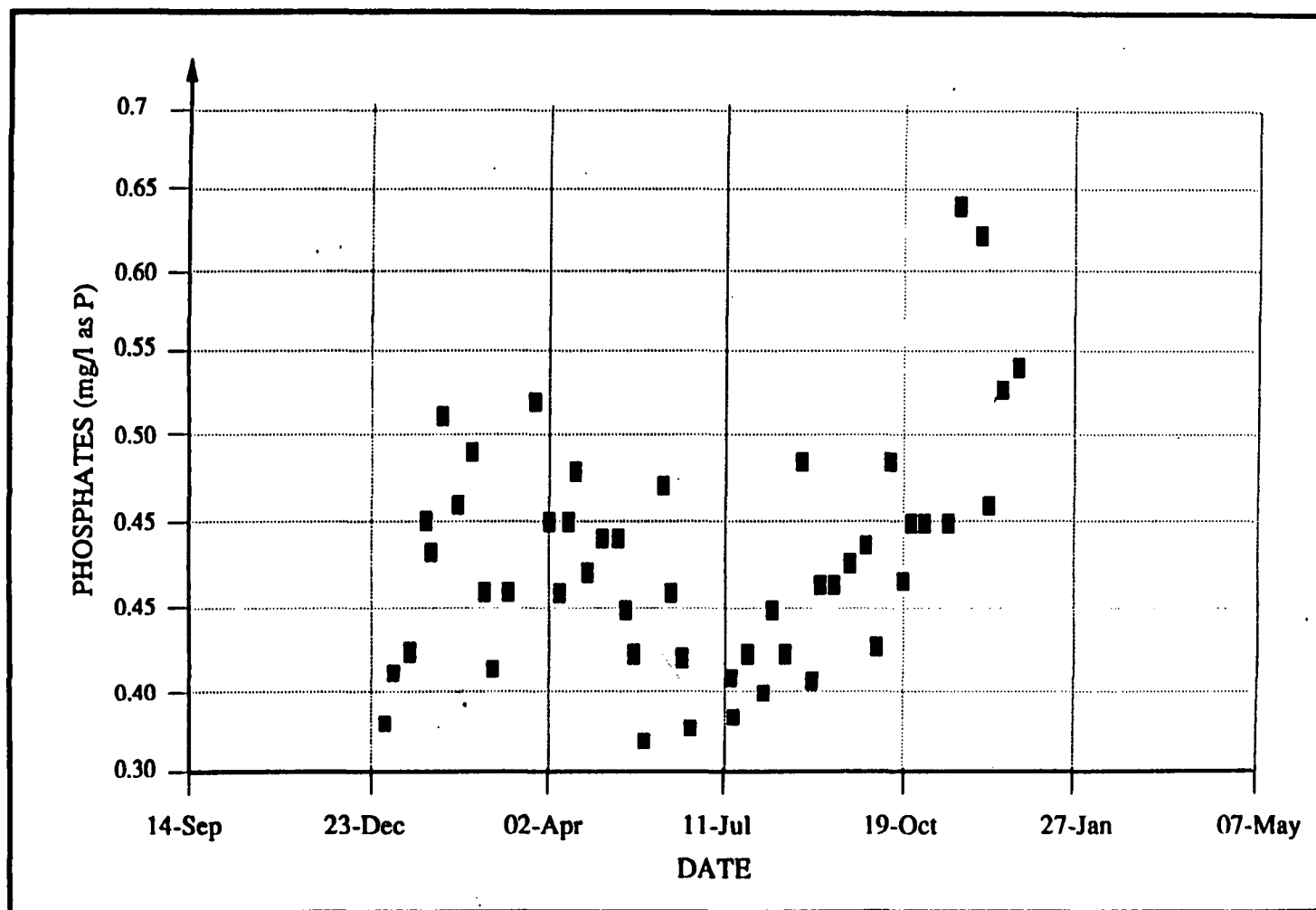
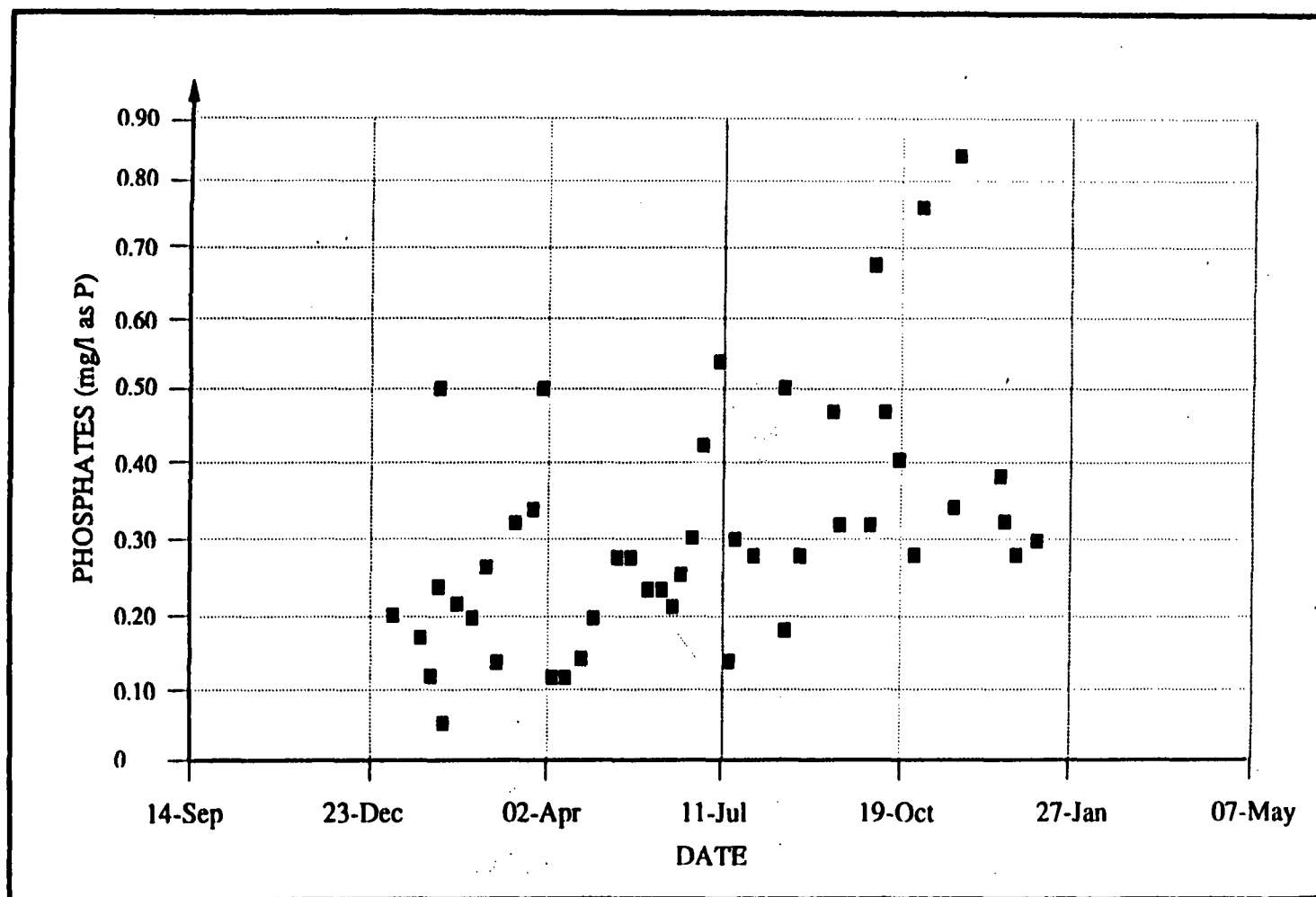


Figure 5-2A. Finished Phosphates vs. Time  
Plant D



**Figure 5-2B. Finished Phosphates vs. Time  
Plant H**



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throughout the distribution system—twice every six months—be reported to the States to demonstrate compliance with the established operating conditions. Real-world variability likely to be encountered at water treatment plants should be considered by States in setting these parameters. To accommodate this feature of the Rule and still provide reasonable operating criteria, States may want to consider establishing one-sided conditions such as minimum values, for the water quality parameters used to describe the optimal treatment process.

For example, assume that a PWS using carbonate passivation as optimal corrosion control treatment initially set water quality goals for its finished water as follows:

pH = 7.8 - 8.0  
Alkalinity = 40 - 50 mg/L  $\text{CaCO}_3$   
Total Hardness =  $\geq 30$  mg/L  $\text{CaCO}_3$

During the year of follow-up monitoring, the PWS monitored the finished water for each of these parameters four times a day. The results of this monitoring resulted in the following range of values for each water quality parameter:

pH = 7.65 - 8.21  
Alkalinity = 37 - 46 mg/L  $\text{CaCO}_3$   
Total Hardness = 32 - 56 mg/L  $\text{CaCO}_3$

In this case, the State set as operating criteria for the PWS a minimum pH value of 7.6; minimum alkalinity of 35 mg/L  $\text{CaCO}_3$ ; and a minimum hardness of 30 mg/L  $\text{CaCO}_3$ .

For a PWS which practices softening and tries to establish a calcium carbonate precipitation, setting water quality criteria by the pH, alkalinity, and calcium levels

independently may be irrelevant to the successful formation of calcium carbonate deposits. States should set minimum water quality parameters such that the PWS can achieve finished water pH, alkalinity, and calcium levels which produce a targeted range in calcium carbonate precipitation potential (CCPP) values. Those systems should include in their reporting data the calculated CCPP value for each monitoring event during the reporting period.

For example, a lime softening system experiences large variability in raw water calcium hardness and alkalinity at different times of the year. The softened water quality also reflects this variability. However, the system can control the finished water pH leaving the plant through its recarbonation process. After reviewing the historical treated water quality, the PWS found that the range for final calcium hardness and alkalinity each was 80 - 160 mg  $\text{CaCO}_3$ /L. The PWS determined that the CCPP target value was 12 mg  $\text{CaCO}_3$ /L for optimal corrosion control treatment. Based on these observations, the PWS calculated the final pH needed to reach the targeted CCPP level based on variable calcium and alkalinity contents as shown below.

The State set the operating guidelines the system based on the above information as follows:

Minimum Alkalinity and

Calcium Hardness = 80 mg  $\text{CaCO}_3$ /L  
Minimum pH = 7.8 units  
Average CCPP Value = 12 mg  $\text{CaCO}_3$ /L

When inhibitors are applied as the method of corrosion control treatment, minimum finished water inhibitor levels should be included in the operating criteria set by the State. In addition, the finished

**Table 5-3. Operating Guidelines for Final pH to Meet a CCPP Level of 12 mg/L**

Treated Water Alkalinity mg CaCO <sub>3</sub> /L	Treated Water Calcium Hardness, mg CaCO <sub>3</sub> /L		
	80	120	160
80	9.2	9.1	9.0
100	9.0	8.9	8.7
120	8.9	8.6	8.3
140	8.7	8.3	8.0
160	8.5	8.0	7.8

water pH is often important to the performance of the specific corrosion inhibitor, and thus an operating criteria for pH is also required. The results of the follow-up monitoring should be evaluated to determine the minimum inhibitor dosage needed to provide an effective residual inhibitor level throughout the distribution system. States should recognize that the introduction of inhibitors into distribution systems can cause initial disturbances in the existing corrosion byproducts and thereby reduce the aesthetic quality of the delivered water to the consumer. Therefore, many PWSs may begin inhibitor treatment with elevated or reduced inhibitor dosages (as compared to that recommended for optimal treatment) in order to cause the least distribution system upset during this initial conditioning period.

In reviewing the follow-up data for inhibitor applications, States should evaluate the inhibitor-demand exerted throughout the distribution system. The inhibitor-demand is the depletion of inhibitor concentration from the points of

entry to the distribution system to the locations where water quality parameters monitoring occurs (or the dose minus the residual concentration). Since water systems may either over-dose or under-dose initially, the minimum dosage required by the State should be equivalent to the average inhibitor demand found during follow-up monitoring plus the concentration of an effective inhibitor residual. For example, if a PWS found that the average orthophosphate demand within its distribution system during follow-up sampling was 0.5 mg PO<sub>4</sub>/L, the State may require a minimum dosage of 0.8 mg PO<sub>4</sub>/L to produce an residual orthophosphate residual of 0.3 mg PO<sub>4</sub>/L throughout the distribution system.

### **5.2.3 Diagnostic Sampling.**

The LCR has specific monitoring requirements for initial monitoring, follow-up monitoring, and reduced monitoring. Specified periods in which to monitor as well as certain sampling and testing procedures all must be followed for tap

samples and water quality parameters at points of entry and within the distribution system. Additional sampling, however, should be considered by the PWSs. Termed diagnostic sampling, the purpose of additional sampling and monitoring would be to assist in defining problems so that proper corrective action could be taken. Gathering additional information early in the process can be the key to successfully meeting the lead and copper ALs during the follow-up monitoring period. These additional data do not need to be reported as part of the compliance monitoring.

Sampling procedures do not need to follow the protocol outlined in the LCR, but instead can be designed to evaluate a specific situation. For example, perhaps a certain sampling location gives abnormally high lead values during the initial monitoring period. The initial first-draw tap sample was a one-liter sample as required by the Rule and was collected at the kitchen sink. Additional sequential 100 mL samples collected at the same tap might show an extremely high lead concentration in the first 100 mL while subsequent samples had low lead levels. Data such as these would tend to indicate a problem with the immediate water fixture which the homeowner could be encouraged to replace.

Additional sampling within the distribution system will almost surely be necessary if the water chemistry is changed or an inhibitor is added. In this case, diagnostic monitoring will help stabilize treated water quality by indicating if chemical feed systems are properly adjusted or if inhibitor concentrations are penetrating throughout the distribution system, for example. Using

diagnostic monitoring to assist in optimizing corrosion control treatment to meet the ALs can aid a PWS by reducing future monitoring, eliminating the need to replace lead service lines, and allowing the public education program to be discontinued.

### ***5.2.4 Operational Notes on Various Treatments.***

Achievement of operating goals is dependent on the raw water quality variability, process control capabilities, chemical feed systems employed, and the equipment used at each PWS. This section discusses aspects of operating a corrosion control treatment program successfully and the various problems which may be encountered based on the chemical feed system used for each treatment approach.

**5.2.4.1 Calcium carbonate precipitation.** With this technique, the concentration of calcium and carbonate ions is such that their solubility is exceeded and calcium carbonate solids precipitate to form a protective coating on the interior pipe walls. In essence, the use of cement-lined metal pipes is an effort to provide a protective lining even if the water quality conditions do not favor calcium carbonate precipitation.

Depending upon water chemistry, it may be necessary to adjust the calcium, carbonate, or hydrogen ion content of the water to form a calcium carbonate film. Calcium supplementation is usually achieved by adding hydrated or quick lime; and carbonate adjustment can be accomplished by adding soda ash, sodium bicarbonate, or carbon dioxide. Hydrogen ion, or pH, adjustment may be accom-

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plished by adding any of these chemicals in addition to other bases or acids such as caustic soda, hydrochloric acid, or sulfuric acid. It is difficult to establish a uniform thickness of calcium carbonate on interior pipe walls throughout the distribution system. If excessive precipitation occurs in some portions of the system, a significant reduction in hydraulic capacity may be experienced.

For large systems, storage silos are provided for solid chemicals, such as lime ( $\text{CaO}$ ), and the bins are equipped with vibrators and compressed air agitators to reduce clumping and promote the flow of chemical into gravimetric or volumetric feeders. The feeders discharge the dry chemical into solution tanks where it is dissolved into water. Lime can have a significant amount of impurities and solution tanks have provisions for collecting and purging inert particles. In some situations, it is more economical to use quicklime, and slake it onsite, rather than purchase hydrated lime directly from the supplier. To use quicklime requires additional equipment to slake the calcium oxide and remove impurities that are contained within the material. As a result, slaking operations are generally used in larger facilities or lime softening plants which use more lime where the investment and operation of such equipment can be justified.

For smaller plants or those requiring low to moderate dosages, hydrated lime is normally used and continuous or semi-continuous solution tanks are more appropriate and economical for large operations. Removal of impurities is still important with hydrated lime, particularly when it is fed downstream of filters or in

situations where no filters are used. Depending upon site-specific design factors, the solutions can be fed to the water by gravity, using weirs or rotodip feeders, or chemical feed pumps.

Lime and soda ash systems require a high degree of operator attention due to calcium carbonate plugging of bins, tanks, pumps, and piping. To reduce the amount of downtime due to such plugging problems, bins must be kept dry and provisions should be made for acid cleaning of the feed systems. Because of this concern, the reliability of dry chemical feed equipment is less than that for liquid systems. Redundancy of solution tanks and chemical feed pumps can reduce the likelihood of extensive treatment interruptions, providing further assurances of continuous corrosion control operations.

Where the natural concentrations of calcium and inorganic carbonate contents are sufficient but the pH is too low for a precipitate to form, sodium hydroxide can be used to increase the pH to the point that calcium carbonate precipitation will occur. Sodium hydroxide is normally delivered as a 50 percent solution and diluted at the time of delivery to 20 to 30 percent. Dilution is helpful in reducing crystallization that can occur at temperatures below 50°F. Indoor storage facilities are normally used even for the diluted sodium hydroxide solution. If dilution is practiced, consideration should be given to ion exchange softening of the dilution water to prevent calcium carbonate plugging of the sodium hydroxide feed system. Employee safety and spill containment are important design concerns with sodium hydroxide systems.

For lime and lime/soda softening systems, lime and soda ash are added at various points throughout the treatment train to remove carbonate and non-carbonate hardness. The final pH is adjusted through carbon dioxide or acid addition to prevent excessive encrustation of filters and still provide the long-term accumulation of a calcium carbonate film within the distribution system pipes. For turbidity removal plants using aluminum or iron salts, the location of lime, soda ash, or bicarbonate feed points should be carefully considered, balancing the water quality requirements for coagulation, filtration, and disinfection performance with that of corrosion control.

In summary, the choice regarding which chemical(s) to use and where to apply them must integrate water chemistry, customer acceptance, cost, reliability, safety, and operator preference issues. Therefore, there is no chemical that is right for all locations and representatives of management, operations, and engineering should be included in the decision-making process.

### **5.2.4.2 Carbonate passivation.**

Carbonate passivation is a corrosion control technique where the pipe materials are incorporated into a metal/hydroxide/carbonate film that protects the pipe. This technique is most suitable for low hardness and alkalinity waters where the PWS does not want to drastically alter the water chemistry, and historic customer acceptance of the water, to the point that calcium carbonate precipitation will occur.

Passivation may be achieved by alkalinity and pH modification using such chemicals as lime, soda ash, sodium bicarbonate,

sodium hydroxide, potassium hydroxide, and/or carbon dioxide. Consequently, the same chemicals and feed systems are used for carbonate passivation as for the calcium carbonate film technique noted above.

**5.2.4.3 Inhibitors.** A wide variety of specialty chemicals, most of them phosphate or silicate based, can be added to the finished water to reduce corrosion within the distribution system. One phosphate-based inhibitor is zinc orthophosphate. With this chemical, it is suspected that the zinc and phosphate components are involved in forming a protective film and providing corrosion protection. With polyphosphate chemicals, direct corrosion protection appears to be minimal except that which may be afforded by the formation of orthophosphate constituents within the distribution system as the polyphosphate reverts to orthophosphate. Sodium silicate is another corrosion inhibitor for which limited performance data is available regarding the reduction of lead and copper corrosion activity.

A potential problem with orthophosphates is that when they are first added to a distribution system, previously corroded material may be released and cause aesthetic problems with the water. This is especially true if the treated water pH is lowered concurrently with the addition of the inhibitor. Additionally, polyphosphates generally will exhibit more of a tendency to remove corrosion byproducts than orthophosphate formulations. Polyphosphates are sometimes used to chemically remove tuberculation and scale. To minimize the potentially negative customer reaction to such a situation, low dosages may be used initially and then

slowly increased to the desired full strength dose. Alternatively, systems may initially feed inhibitor doses much higher than the maintenance level to acclimate the distribution system when concerns about releasing excess corrosion products in the delivered water are not significant. Properly timed public education and flushing programs can also be used to minimize the temporary aesthetic problems that may occur with orthophosphate addition.

No direct evidence is available indicating that the introduction of phosphate-based corrosion inhibitors would foster or encourage the growth of bacteria in the distribution system. Instead, the findings of a number of studies indicate the positive response of distribution system water quality to the implementation of effective corrosion control programs (LeChevalier et al., 1987, 1988a, 1988b, 1990). Microbiological growth within piping systems appears to be more strongly linked to their tendency to grow in conjunction with corrosion byproducts, such as tubercles, than the supplementation of nutrients in the form of phosphates or inorganic carbonate species (AWWARF, 1990). Corrosion control programs which reduce corrosion scale buildup has appeared to reduce the occurrence of bacteria in distribution system water samples.

However, the potential impact of any treatment method on the microbiological behavior of the distribution system is an important consideration. Some testing methods are available for evaluating this impact.

Although not to be interpreted as corrosion control, a primary use of polyphosphates is to sequester dissolved metal

or cationic constituent—such as calcium, iron, or manganese—and reduce their ability to precipitate either in the distribution system or within the water treatment plant. In the case of calcium, polyphosphates are used in many softening plants to minimize the encrustation of filter media by post-precipitation of calcium carbonate. For iron and manganese control, polyphosphates can effectively reduce the aesthetic discoloration caused by these compounds. This is often a useful and necessary benefit of their application, particularly for groundwater systems which are heavily mineralized and devoid of oxygen, ideal conditions for iron and manganese to solubilize. Seasonally high levels of iron and manganese can also occur with surface water supplies when low dissolved oxygen and reducing conditions in upstream reservoirs increase the concentration of these minerals.

While polyphosphates have demonstrated limited direct success toward lead and copper corrosion control, their use at water treatment facilities will be necessary in many instances. New orthopolyphosphate blends are being produced which can offer some of the benefits of both uses to PWSs. These should be considered when orthophosphate inhibitors are a viable corrosion control approach, but a polyphosphate is also required for other treatment objectives.

With respect to chemical feed systems, silicate and phosphate compounds are not inherently dangerous or corrosive, have a long shelf life, and are highly soluble in water. These features allow the use of relatively small batch tanks and feed pumps. If sodium silicates are being used after dilution, the day tanks should be

sized to fully utilize the solubilized silicate within 24 hours to ensure effective application. Since aging times are not needed and short disruptions of service can be tolerated, single tank systems are feasible. For more reliable service, multiple batch tanks with automatic switch-over can be used. Multiple tanks also facilitate cleaning and maintenance of the system.

Depending upon which chemical is selected, the batch tanks may contain a phosphate-rich solution. Since biological growths can occur in the tanks, provisions should be made to routinely clean them. It may also be desirable to provide for supplemental chlorination of the water in the batch tanks to reduce biological growths. Chlorine addition to polyphosphate or ortho-polyphosphate solution water may not be advisable for those situations where sequestering of iron and manganese is important. The chlorine will tend to oxidize these metals, causing some of them to precipitate before they can be sequestered by the polyphosphates. Silicates are not a nutrient and feed system design and maintenance requirements are less than for phosphate-based inhibitors. In fact, some plants have been known to mix silicates and fluoride in the same tank and feed them concurrently using the same pumps. The sodium concentration is also a consideration when sodium silicate is used.

If the PWS desires the inhibitor to also act as a sequestering agent for iron and manganese, chemical addition should occur upstream of the first point where chlorine is added. If iron and manganese are not a problem, the inhibitor can be added to the finished water downstream of chlorination.

### **5.2.5 Reliability.**

The reliability of the various treatment approaches to continuously provide corrosion control protection is not clearly understood with regard to the home plumbing environment. Some limited evidence has indicated that copper corrosion can recur when carbonate passivation treatment is interrupted for very brief periods of time (on the order of a couple of days) (Elmund, 1992). It has also been reported that phosphate-based inhibitors can support longer interruptions prior to reversion of corrosion activity (30 or more days) (Lechner, 1991). However, the Lead and Copper Rule requires that corrosion control treatment be operated at all times. The water quality monitoring is required every two weeks to demonstrate that treatment is continuously provided. Therefore, treatment interruptions due to maintenance, chemical inventory problems, and/or equipment and instrumentation failures must be minimized regardless of the treatment approach selected.

While the goal for system reliability is operational functioning 100 percent of the time, realistic performance may be less than this goal. The design of the full-scale system, however, can incorporate redundancy and/or alarm features which can assist PWSs in maintaining continuous operations.

### **5.2.6 Instrumentation and Control.**

For calcium carbonate precipitation and carbonate passivation, pH is typically used as a real-time instrumentation and control parameter. While pH is an indirect

measurement of calcium carbonate precipitation or carbonate passivation, it is a proven, direct loop control parameter and with experience, the operators can reliably produce finished water with the pH within the range that works best for a particular system. Although specific ion probes are available for calcium, carbonate is most commonly measured by a titration process. While calcium content or pH can be used for on-line monitoring and chemical feed control, they may be correlated to such corrosion monitors as lead and copper levels in tap sampling programs, or test results from coupons or pipe inserts from the distribution system.

For inhibitors, the treatment goals typically concern only the applied dosage. Therefore, pacing chemical feed according to flow and routinely checking for system residuals of the inhibitor may be sufficient operational control. Through the corrosion control study, PWSs may determine the residual concentration that minimizes corrosion, cost, and undesirable side effects. If a higher level of operational control is desired, it may be possible to tie the inhibitor feed pump to a corrosion activity monitor utilizing electronic measurement techniques with settings predetermined for optimal corrosion control conditions.

### ***5.2.7 Troubleshooting.***

The purity of the chemicals used for corrosion control treatment can vary, especially for hydrated lime and quicklime. These chemicals will contain inert material which must be removed through a de-gritting process, and an allowance for inert material must be made when establishing chemical feed rates. For

example, the amount of impurities in quicklime can vary from 4 to 30 percent, with a typical value of 10 percent for municipal grade lime. If a PWS determines that the quicklime they are using contains 90 percent calcium oxide (i.e. 10 percent impurities), an additional 11 percent of the bulk chemical must be added to achieve the desired lime dose ( $100/90 = 1.11$ , i.e., 11 percent additional). The purity factors are better for hydrated lime which may only contain 1 to 5 percent impurities, and better still for soda ash which may only contain 1 to 2 percent impurities.

Purity factors are less of a concern with sodium hydroxide and corrosion inhibitors. There are many proprietary corrosion inhibitors, particularly for the phosphate group of chemicals. While these chemicals may be effective, PWSs may not always know the exact amount and type of compounds contained in the product. Suppliers should submit documentation that their products are safe to use in a potable water application. In some situations, Food and Drug Administration approvals are appropriate. In other cases, the general type of chemical will be listed by the Code of Federal Regulations as a "...substance generally recognized as safe."

Each State has a drinking water direct additives program which follows either the National Sanitation Foundation Health Effects Standard 60 or its own standards for judging the suitability of direct additives for potable use. Any corrosion control chemical used at a PWS must comply with the State's direct additives program requirements.

Staffing requirements may increase with the implementation of corrosion control treatment and additional testing



required by the Lead and Copper Rule. Due to the factors noted above, labor and maintenance requirements may be higher for calcium carbonate precipitation and carbonate passivation than for the addition of a corrosion inhibitor. Regardless, PWSs that are required to provide optimal corrosion control treatment need to schedule and budget for the additional staff that may be needed. The schedule presented in Table 5-1 can be used to coordinate hiring and training requirements in advance of the dates when corrosion control treatment is required to be on line.

Recognizing that problems may occur with the startup of any new treatment component, PWSs should collect appropriate data and analyze the trends that occur. One of the unique issues about corrosion control is that a substantial amount of time may elapse between the time treatment changes are made and their effects are detected through the analysis of tap samples or corrosion monitors. For this reason, detailed recordkeeping procedures should be developed and followed to correlate proper control of the treatment processes with the desired effects in the distribution system.

Important records will include customer complaints such as colored water, stained fixtures or laundry, taste and odor problems, and the lack of water pressure. These records should also include data regarding the age of the house, type of interior and exterior plumbing, and the utilization of onsite point of use (POU) equipment such as softeners or carbon filtration systems. The PWS's follow-up action to the customer complaint should also be noted in the records.

### ***5.3 Optimization Techniques***

Optimization of corrosion control treatment encumbers two overall phases: (1) diagnosis of the need for optimization; and (2) methods for implementing optimization techniques and addressing the possible outcomes from such actions.

#### ***5.3.1 Diagnosing the Need for Optimization.***

Many PWSs may install optimal corrosion control treatment and still experience excessive lead, copper, or other corrosion byproducts in the delivered water. Determining when treatment has been optimized—i.e., providing the maximum corrosion protection possible through water treatment—is the first step. Additional sampling and monitoring (see Diagnostic Monitoring, Section 5.2.3) should be used to assist in optimizing corrosion control treatment. Monitoring during the two-year installation period can be an important key in meeting ALs during subsequent compliance monitoring periods, and data collected during this two-year period do not have to be reported to the State. PWSs should consider monitoring for the appropriate water quality parameters at the entry point(s) to the distribution system as well as within the distribution system. Collecting tap samples for lead and copper determinations will assist in maintaining contact with homeowners who assisted during the initial monitoring phase as well as providing important information regarding improvements to water quality resulting from the corrosion control treatment.

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Since corrosion control practices to minimize lead and copper levels in first-draw tap samples has not been generally practiced by the drinking water community, little information is available demonstrating the performance of treatment optimization techniques. Therefore, PWSs must approach optimization with caution, allowing sufficient time for treatment to become effective and stabilize before implementing any changes in an attempt to improve system performance.

Data collection efforts regarding the corrosion behavior of the distribution system and home plumbing environments should be used to develop long-term trends in system behavior. Given the variability in corrosion activity, observations of improvements in corrosion protection should be confirmed by at least one year of monitoring data before any changes are considered. However, distribution system upsets by the installation of corrosion control treatment—such as the release of existing corrosion byproducts when inhibitors are first applied—may be realized very quickly after startup of treatment. When degradation of water quality in the distribution system and at consumers' taps occurs, a timely response should be made by PWSs to address these problems.

The following steps should be addressed in the priority shown to logically progress through optimization of the installed treatment process:

- Step 1 - Select treatment chemicals which enable the WTP to meet its optimal corrosion control treatment objectives;
- Step 2 - Select chemical application points within the WTP to provide

optimal utilization of each chemical additive;

- Step 3 - Reduce water quality parameter variability at the points of entry to the distribution system;
- Step 4 - Reduce water quality parameter variability within the distribution system;
- Step 5 - Modify the water quality parameter goals that define optimal corrosion control treatment and thereby the chemical feed requirements.

Steps 1 and 2 should be addressed initially during the corrosion control study; however, changes in other water treatment processes or the need to improve corrosion control performance may cause their reevaluation. Steps 3 and 4 focus on the ability of the WTP and distribution system to be operated in accordance with the corrosion control treatment goals. In many cases, optimization for PWSs will consist of addressing these conditions. Maintaining consistent water quality leaving plants and within distribution systems can be difficult, and optimizing treatment without such control may not be possible. Step 5 relies on changing the actual goals defining that treatment for optimization, and should only be pursued as the last option by PWSs and must be approved by the State.

Any change in treatment or plant operations can impart adverse effects on other water treatment or water quality goals. General relationships may be described to illustrate the effect of water quality changes on treatment and finished water quality objectives. Table 5-4 identifies the major water quality characteristics of concern and provides a general indication of their influence and effects. Decisions related to corrosion control

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**Table 5-4. Relational Behavior of Changing Water Quality Conditions for Corrosion Control Treatment and Other Water Quality/Treatment Objectives**

Water Quality Change	Impact
<b>Non-Softening WTPs:</b>  <b>pH Increase - After Filtration</b>	<ul style="list-style-type: none"> <li>• Increase in TTHM formation.</li> <li>• Decrease in haloacetic acid formation.</li> <li>• Increase in final turbidity when lime is used.</li> <li>• Reduced disinfection efficacy.</li> <li>• Post-filtration precipitation of manganese.</li> </ul>
<b>Softening and Non-Softening WTPs:</b>  <b>pH Increase - Before Filtration</b>	<ul style="list-style-type: none"> <li>• Reduced disinfection by-product precursor removal when alum coagulation is practiced.</li> <li>• Increase in TTHM formation.</li> <li>• Decrease in haloacetic acid formation.</li> <li>• Reduced disinfection efficacy unless at pH levels above 9.0.</li> <li>• Increased soluble aluminum levels when alum coagulation is practiced.</li> <li>• Increased removal of manganese.</li> <li>• Increased encrustation of filter media when excess calcium carbonate available.</li> <li>• Excess precipitation of calcium carbonate when available in pipe network near WTP.</li> </ul>
<b>Softening WTPs:</b>  <b>pH Decrease - Before Filtration</b>	<ul style="list-style-type: none"> <li>• Decrease in TTHM formation.</li> <li>• Increase in haloacetic acid formation.</li> <li>• Reduced encrustation of filter media.</li> <li>• Reduced soluble aluminum levels when alum is added during softening.</li> </ul>
<b>Alkalinity Increase</b>	<ul style="list-style-type: none"> <li>• Increase ozone demand for disinfection.</li> </ul>
<b>Alkalinity Decrease</b>	<ul style="list-style-type: none"> <li>• At very low levels, reduced coagulation performance when using alum.</li> </ul>
<b>Calcium Increase</b>	<ul style="list-style-type: none"> <li>• Increased encrustation of filter media when excess calcium carbonate available.</li> <li>• Excess precipitation of calcium carbonate when available in pipe network near WTP.</li> <li>• Increase scavenging of phosphate inhibitors used for either corrosion control or chelation.</li> <li>• If after filtration, finished water turbidity increases.</li> </ul>
<b>Calcium Decrease (Softening WTPs)</b>	<ul style="list-style-type: none"> <li>• Prevent excess precipitation of calcium carbonate in pipe network near WTP.</li> </ul>
<b>Phosphate Increase</b>	<ul style="list-style-type: none"> <li>• Stripping of existing corrosion by-products in the distribution system causing aesthetic quality degradation and increasing HPC levels initially due to biofilm disturbances.</li> </ul>
<b>Silicate Increase</b>	<ul style="list-style-type: none"> <li>• May reduce useful life of domestic hot water heaters due to "glassification"; silicates precipitate rapidly at higher temperatures.</li> </ul>

optimization should not be based solely on the limited information presented in Table 5-4. This table is more appropriately used as a screening tool and a vehicle for focusing current and future investigative efforts in developing optimization approaches.

### **5.3.2 Methods for Evaluating Treatment.**

Identifying the corrosion behavior of the distribution system and home plumbing environments after the implementation of optimal corrosion control treatment is necessary to determine whether potential improvements may be made by optimizing corrosion control treatment. The methods discussed in this section may assist PWSs in developing long-term trends in corrosion control performance. Not all data collection efforts are necessary, but PWSs should consider more than one method for evaluating the actual performance of treatment since no single technique can completely describe the variety of corrosion activity and its possible causes.

#### **5.3.2.1 Water quality parameters.**

After implementing an optimal corrosion control program, follow-up monitoring is required for pH, alkalinity, and calcium for all large PWSs and those small and medium-size PWSs that exceed an AL. In addition, orthophosphate or silica monitoring is also mandatory if one of these corrosion inhibitors is used. To assist in the optimization process, PWSs are encouraged to measure these water quality parameters in the tap samples collected from consumers' homes. This would be useful in tracking both the success of the corrosion control program and the

alteration of water quality within consumers' plumbing systems.

Increases in THM formation are observed with increasing pH and this may be a concern for those systems where the pH is increased as part of the corrosion control program. Therefore, additional THM testing within the distribution system may give insight about whether further adjustments can or should be made in the finished water pH.

Microbiological activity within the distribution system should be closely monitored after installing corrosion control treatment. Several studies investigating the impact of corrosion control on the behavior of biofilms have generally concluded that reductions in corrosion activity significantly reduces: (1) the likelihood of biofilm growth; and (2) the resistance of microorganisms to disinfectants. The additional nutrients which may be added as a result of corrosion control treatment has not been shown to increase the biological activity of the distribution system. Total coliform monitoring as required by the Total Coliform Rule and regular testing for heterotrophic plate count bacteria would assist PWSs in understanding the response of the distribution system to corrosion control treatment.

**5.3.2.2 Lead and copper data.** All PWSs required to install corrosion control treatment must perform routine monitoring of first-draw tap samples for lead and copper. These data may be used to determine the long-term effectiveness of corrosion control treatment and the ongoing actions required by the Rule, such as public education or lead service line replacement programs.

As a check on the consistency of the treatment process and the impact of varying hydraulic conditions and water blends within the distribution system, the PWS may find it useful to collect first-draw samples for five or more consecutive days at a representative number of sites prior to the start of the follow-up monitoring period. The additional tests should be considered diagnostic monitoring (Section 5.2.3) rather than compliance sampling. If the lead and copper results from a particular tap vary significantly from day-to-day, it indicates that the corrosion control program is not achieving consistent results in that location. Depending upon how widespread the inconsistencies are, the PWS should investigate whether chemical feed problems, variations in raw water source, hydraulic changes in the distribution system, or site-specific conditions are contributing to the daily variation in lead and copper values. The goal of such additional testing is to ensure that corrosion control objectives are consistently met at all times.

### **5.3.2.3 Coupons and pipe inserts.**

Coupons are available in a variety of metals, such as lead, copper, cast iron, bronze, and mild steel. Mild steel and copper coupons are most frequently used. Typically, coupons are placed in 8-inch or larger pipes and in locations that have moderate flow velocities (2-6 fps). Coupon locations should avoid both stagnant and high velocity flow conditions that are not representative of the system as a whole.

When properly placed within the distribution system, coupons provide a direct indication of corrosion rates within the pipe network. Some of their limitations,

however, include the fact that it takes a long time to obtain accurate values and coupons cannot be used to indicate short-term changes in water quality characteristics. For example, multiple coupons should be used at each site so that corrosion rates over varying lengths of exposure time may be measured. This also provides information regarding the impact of seasonal variations on corrosion activity. In addition, while the coupon insertion and removal equipment is moderately priced, additional costs may be incurred to construct access vaults at the locations where coupons should be placed. Finally, coupons are typically located within the main pipe network and this is not necessarily representative of the home plumbing environment which lead and copper monitoring reflects.

In summary, coupons can provide meaningful information regarding the rate at which exposed metal will corrode or become encrusted with scale-forming deposits within distribution system piping networks. As such, PWSs should consider their use as part of a comprehensive corrosion monitoring program but should not rely solely on these measures to assess corrosion control performance.

Pipe inserts are small segments of uncoated metal pipe that are part of the distribution system. Inserts can be placed in a vault that includes a bypass line so the insert can be removed from service and inspected for corrosion or deposition. Inserts provide the opportunity to see what is happening to the pipe wall itself, rather than pieces of metal inserted into the pipe. By coring or cutting sections from the pipe, the thickness of the remaining metal or deposit can be directly measured. Ultra-

sonic instruments are also available to indirectly measure the thickness of the metal and/or deposit.

Pipe inserts suffer many of the same limitations as coupons since they must remain in place for long periods of time, may be expensive to install and remove, and are not representative of home plumbing conditions. As with coupons, however, pipe inserts can provide relative information on the effectiveness of a corrosion control program.

**5.3.2.4 Corrosion indices.** Corrosion indices have been used within the drinking water community to assess the likelihood of forming calcium carbonate scales on pipes, and are derived from calcium carbonate equilibrium relationships. Limitations of the usefulness of these indices needs to be recognized. When optimal treatment consists of calcium carbonate precipitation, indices may properly describe the mechanisms of corrosion control desired. However, the equilibrium relationships upon which most indices are based do not hold true when any inhibitor is present, including polyphosphates which are typically used to prevent metals and/or calcium from precipitating (in the case of many softening plants, polyphosphates are applied before filtration to keep the filters from becoming encrusted by calcium carbonate). Corrosion indices have little merit for those PWSs applying carbonate or inhibitor passivation as corrosion control treatment, and should not be used to describe treatment goals. For calcium carbonate precipitation treatment, the CCPP index is recommended and Appendix A provides a detailed description of its calculation methods.

**5.3.2.5 Corrosion monitors.** There are several means for making discrete observation or measurement of corrosion. These include X-ray, ultrasonic, visual, and destructive testing. While each of these measurement techniques may be useful in a particular situation, this section will focus on electronic monitoring systems which can be used while the distribution system is in operation. Some of the electronic monitoring devices measure the byproducts of galvanic corrosion and others will detect the loss of metal whether it is due to galvanic action, leaching, or some other corrosion mechanism.

**5.3.2.5.1 Hydrogen probes.** As part of the oxidation/reduction reaction in acidic solutions, hydrogen atoms will migrate to cathode sites on the inside surface of metal pipes. One type of probe allows these hydrogen atoms to penetrate, combine, and form hydrogen gas. The gas will exert pressure which is proportional to the amount of galvanic corrosion that is occurring within pipeline. Another type of probe uses palladium foil to create an electrical output which is directly proportional to the hydrogen evolution rate. By recording pressure reading or electrical output trends, changes in the corrosion rate can be detected.

**5.3.2.5.2 Electrical resistance.** This type of instrument measures the electrical resistance of a thin metal probe inserted into the pipeline. Compared to conventional coupons, electrical resistance probes provide results with a minimal amount of effort. Continuous readings can be made and the data analyzed to identify corrosion trends. For example, an increase

in electrical resistance would likely indicate an increase in corrosion rates.

**5.3.2.5.3 Linear polarization resistance.** In a galvanic corrosion cell, the pipe metal is oxidized, or corroded, at the anode and cations in the solution are reduced at the cathode. In this process, electrons are transferred between anodic and cathodic areas on the corroding metal. When a small voltage potential is applied across the electrolyte fluid, the electrical resistance is linear and the corrosion current flow (corrosion rate) is directly proportional to the measured current flow. In dilute solutions such as drinking water, the resistance of the electrolyte can be significant compared to the polarization resistance of the anode and cathode sites. In these situations, the probe must be of the type that will measure and compensate for the resistance of the solution.

Compared to metal coupon and electrical resistance monitoring, linear polarization probes provide a direct reading of the corrosion current and rate. This allows for instantaneous measurement of the changes that occur with the type and amount of corrosion control chemicals that are added to the water. Linear polarization measurements, however, cannot be made in non-conductive fluids or those which coat the electrodes. Therefore, they may not be appropriate in those situations where a calcium carbonate film is used to coat the distribution system.

**5.3.2.5.4 Electrochemical noise.** This is a monitoring technique which measures the electrochemical disturbances created by corrosion activity. Potential limitations include the fact that other sources of electrical disturbance, such as

those from an impressed current system, can result in overestimates of the corrosion rate. This technique, however, is used by some equipment manufacturers to indicate the "pitting index" for a particular pipe-line/electrolyte combination.

**5.3.2.5.5 Application suggestions.** Electronic corrosion monitoring equipment can provide a rapid evaluation of corrosion control treatment alternatives and chemical feed rates. These probes are not infallible, however, and the electronic measurements need to be correlated with the results from other indicators such as lead and copper data, conventional coupons, pipe inserts, and water quality indices. Once the relationship between electronic measurements and actual field corrosion conditions is established, corrosion monitors can be a useful tool for monitoring plant performance and maintaining the finished water within the operating parameters discussed in Section 5.2.2.

## ***5.4 Optimizing Corrosion Control Treatment—Examples***

Each PWS will experience unique circumstances surrounding the optimization of corrosion control treatment based on site-specific conditions, treatment objectives, and other considerations affecting the performance and operation of the distribution system. The following examples illustrate the types of problems which PWSs may encounter and approaches to solve treatment and operational concerns.

### ***5.4.1 Optimal Corrosion Control in a Consecutive System.***

East Bumford County runs a surface water filtration plant that delivers water to a number of small and medium-size towns. To more efficiently implement the rule, the towns petitioned and received approval to have the county water treatment plant and the entire distribution system be considered as a consolidated large water system.

As part of the consolidation, East Bumford County agreed to be responsible for implementing the provisions of the Lead and Copper Rule. All water treatment, sampling, and monitoring costs were to be paid for by the County with reimbursement by the towns on a population-weighted basis. Additionally, any lead service line replacements were to be paid for by the town in which they were being replaced.

Addition of a phosphate inhibitor to the water treatment plant effluent was approved by the state as optimal corrosion control. While conducting follow-up monitoring to determine their optimal corrosion control parameters, the consolidated system was found to have met both the lead and copper action levels. However, East Bumford County found that the water in a remote section of Wakuska Township was not maintaining a phosphate residual. Apparently, the long residence time between the treatment plant and the remote section of Wakuska caused its depletion.

At a subsequent meeting of East Bumford County's member communities, an agreement was reached whereby

Wakuska Township would pay for a chemical feed station to supplement the phosphate inhibitor in their distribution system. It was located downstream of Wakuska's storage reservoir after the Town's master flowmeter. Wakuska Township agreed to pay all costs associated with the chemical feed station and East Bumford County agreed to provide operational and maintenance support.

During the subsequent round of routine monitoring, effective residual phosphate concentrations were achieved throughout the entire consolidated distribution system. This permitted East Bumford County and its member communities to comply with the State-specified operating ranges under the Lead and Copper Rule.

### ***5.4.2 Use of Corrosion Monitors in a Large System.***

As a large system with historical corrosion problems, Plimpton City had been experimenting with control strategies for a number of years. The City found that it could reduce the number of red water complaints if the lime-softening plant was operated to achieve a CCPP index of 6 mg/L CaCO<sub>3</sub> in the plant effluent. Even with this operation, though, the distribution system still experienced some red water, and early initial monitoring results showed that the system would not meet the lead action levels.

Realizing that their attempts at corrosion control to date would not satisfy the provisions of the LCR, the City supplemented their existing program by installing linear polarization resistance corrosion control monitors in different areas of the distribution system before the beginning of the second round of initial



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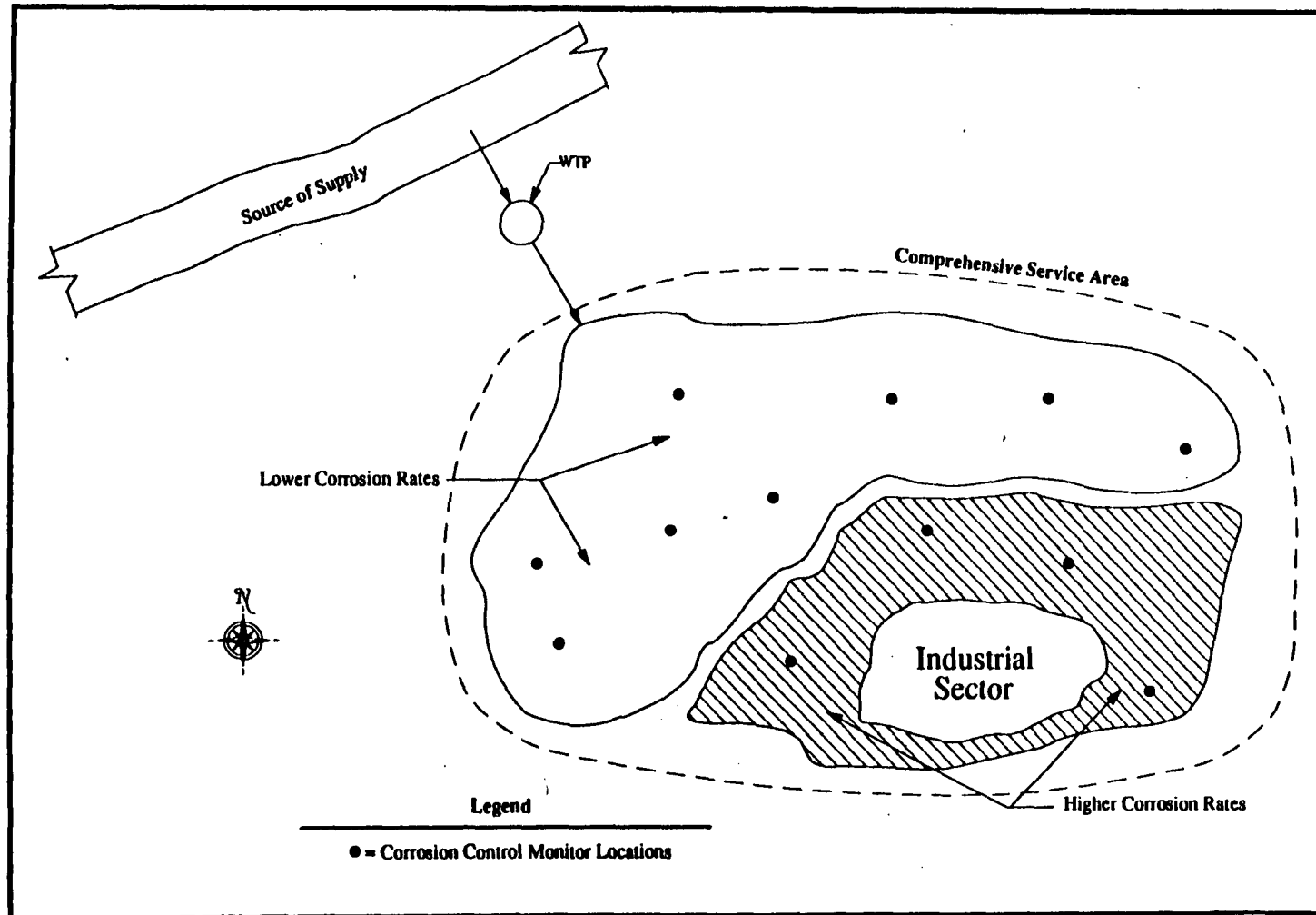
monitoring for lead and copper. Figure 5-3 shows where the monitors were located. The control monitors used iron electrodes to simulate the material in the actual system piping.

Results from the corrosion monitors indicated that the highest corrosion rates were found in the southeast section of the City. However, those rates were not consistently higher, but often fell to the levels found in other areas of the city. The city realized that the southeast corner contained a large industrial sector, causing the distribution system to experience wide fluctuations in localized demand. This resulted in significantly higher velocities passing through the pipes in that area of the city. Since water quality characteristics remained fairly consistent throughout the entire distribution system, the elevated corrosion rates in the southeast zone was attributed to the intermittently high velocities experienced in that area. This effect appeared to be causing disturbances to the coating on the pipes by either physically stripping the precipitated layer, or preventing the water in the pipe from attaining an equilibrium condition under which a calcium carbonate film could be maintained.

To address this concern, the City installed a 5 million gallon storage tank to service the southeast portion of the distribution system. The storage tank allowed the industries to satisfy their peak demands without causing wide velocity fluctuations in adjoining areas. After the tank's installation, corrosion rates in the southeast section corresponded more closely with rates in the other areas of the City.

While the storage tank was being installed, the City began their required corrosion control study. Pipe-loop systems were set up in the treatment plant's existing filter gallery. The same type of linear polarization resistance monitors used in the distribution system were also used in the study. Corrosion rates were monitored not only in iron electrodes, but lead electrodes as well. The series of runs which were conducted allowed for the comparison of corrosion rates of waters with different CCPP indices. As the treatment plant had discovered years earlier, iron corrosion was not much further reduced as the CCPP index rose above 6.0 mg/L  $\text{CaCO}_3$ . However, lead corrosion reached a minimum at 9.5 mg/L  $\text{CaCO}_3$ .

Before the City began full-scale treatment changes to reflect the new CCPP index, they replaced selected iron electrodes in the distribution system with lead electrodes. When they then changed the main plant treatment, they were able to verify that lead corrosion was reduced when the distribution system was receiving water with a higher CCPP index, and that iron corrosion remained at the same levels as when the system received water with the lower CCPP index. Although the lead corrosion rates were lower than they had been previously, they were not quite as low as the pipe-loop study indicated they could be. The pipe-loop system is still being used to determine whether another parameter might more clearly define optimal treatment, and periodic modifications are being made to the pipe-loop in a continuing attempt to model actual distribution system conditions.



**Figure 5-3. Example 5.4.2. — Use of Corrosion Monitors in the Plimpton City Distribution System**

### 5.4.3 Use of Extra Monitoring.

Corrosion studies in the small town of Gechlik Mills showed that raising the pH of their direct groundwater supply from 7.2 to 7.8 caused a dramatic decrease in distribution system lead and copper levels. Direct in-line injection of caustic soda at their two wellheads to achieve a pH of 7.8 was designated as the town's optimal corrosion control. Since facilities to house chemical feeds already existed for sodium hypochlorite, installing the caustic soda system was able to be completed quickly. The Town made arrangements for a chemical company to fill the chemical feed tanks biweekly with a 50 percent caustic soda solution that was directly injected at the wellheads. The Town began using the new system six months ahead of the mandated schedule for treatment installation by the LCR.

The early installation allowed Gechlik Mills six months before they had to collect any lead and copper tap samples. However, the Town began monitoring not only the lead and copper levels, but also water quality parameters at selective distribution system sites to verify that the treatment was working correctly. Many sites were found to experience wide fluctuations in pH over time. Lead and copper levels also fluctuated, and a large number of samples continued to exceed the action levels.

By running a series of bench-scale tests, the caustic soda was found to be working as desired. However, very precise amounts had to be used in order to achieve the 7.8 pH. Although the amounts of the 50 percent caustic soda which had to be added were not very large, substantial pH fluctuations often resulted due to slight variations in feeding. By using larger

amounts of a more dilute caustic solution, similar misfeedings were not found to have as pronounced an effect on pH.

Before the follow-up monitoring period was to begin, Gechlik Mills had already installed larger caustic holding tanks, and had begun injecting a 25 percent caustic soda solution. In the subsequent monitoring round, pH monitoring was conducted along with the lead and copper monitoring. The pH monitoring was found to be unnecessary for Lead and Copper Rule compliance, since the lead and copper monitoring showed that both action levels had been met. Although Gechlik Mills is not always required to, they routinely monitor their distribution system pH in order to troubleshoot any potential increases in corrosion activity.

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## Chapter 6.0 — Lead Service Line Replacement

### **6.1 Overview of LSL Replacement Requirements**

Lead Service Lines (LSLs) have been shown to contribute significant amounts of lead to drinking water at the consumer's tap. Corrosion control techniques are often effective in minimizing lead levels associated with LSLs by establishing a protective coating on the interior pipe surface. Although EPA believes that corrosion control treatment will be the primary means of lead level reduction for the majority of water systems, the establishment of such protection can vary from house to house. In many instances, corrosion control and/or source water treatment alone will not be sufficient to reduce lead levels below the lead AL. In such cases a PWS must replace its LSLs in accordance with the LSLRP requirements (§141.84). EPA believes that the progressive replacement of LSLs which contribute to lead levels above 0.015 mg/L will reduce adverse health risks imposed by lead exposure.

The Lead Service Line Replacement Program (LSLRP) in the June 7, 1991 rule is premised on five principles: (1) corrosion control can reduce lead levels from LSLs in some instances, but high levels may persist after treatment; (2) a system is triggered into a LSLRP if the system exceeds the lead AL after installing optimal corrosion control and source water treatment (follow-up monitoring); (3) water systems should only be responsible for

removing that portion of each LSL they control; (4) a system is not required to physically replace individual LSLs if direct sample lead concentrations are 0.015 mg/L or less and (5) water systems must annually replace at least 7 percent of the total number of LSLs in place at the beginning of the LSLRP.

Any water system that continues to exceed the lead AL after implementing optimal corrosion control treatment and/or source water treatment (whichever is installed later), or during any subsequent monitoring period, must begin replacing LSLs identified within the distribution system. The LSLRP begins on the date the system exceeds the lead AL as referenced above (i.e., January 1 or July 1 of a given year). The State also has the authority to require LSLRP commencement immediately for systems who have failed to install source water or corrosion control treatment by the deadline for follow-up monitoring as provided in §141.86(d)(2).

A water system which is triggered into the LSLRP is required to take three steps: (1) conduct a comprehensive materials evaluation (if not already completed) to identify all homes or buildings served by LSLs; (2) establish a schedule for replacing LSLs; and (3) physically replace all LSLs controlled by the system. Water systems can avoid replacing individual LSLs that are shown to contribute 0.015 mg/L or less to tap water lead levels as measured in LSL samples. Water systems can discontinue the LSLRP if they demonstrate that the lead levels in first-draw water collected

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at targeted taps are below the lead AL for two consecutive six-month monitoring periods. If a system subsequently exceeds the lead AL during any monitoring period, the LSLRP must be recommenced.

The following sections discuss the rationale of the LSLRP requirements, LSL control and related requirements, materials evaluation, LSL replacement schedules, and reporting/record-keeping requirements.

### ***6.2 LSL Control and Related Requirements***

EPA believes its authority to impose regulatory requirements on PWSs extends only to those distribution facilities under the control of the PWS. Under the Rule, systems replacing LSLs are required to replace the portions of LSLs under their control, presuming that the system controls the entire LSL (up to the building inlet). PWSs may rebut the presumption that they control the entire lead service line and replace only that portion which an appropriate legal authority (i.e., State statute, municipal ordinance, public service contract, etc.) defines as controlled by the PWS. The definition of control is discussed in the following subsection and is followed by explanations of the requirements for control presumption rebuttal and partial LSL replacement.

#### ***6.2.1 LSL Control Determination.***

Control is defined in §141.84(e) as one of the following forms of authority:

- Authority to set standards for construction, repair, or maintenance of the line;

- Authority to replace, repair, or maintain the service line; and,
- Ownership of the line.

EPA acknowledges that ownership and/or control of LSLs is often split between the PWS and the property owner. Depending upon State laws or municipal ordinances, some public water systems control and/or own connections up to the property line, others control and/or own the LSL and other connections up to the building, and still others control and/or own the service connections only up to the curb (see Figure 6-1). It should be noted that a lead gooseneck is part of the LSL only when it is attached to the LSL. Where LSL ownership is split between the utility and the user, utilities sometime retain authority to prescribe the standards for construction, repair, and maintenance of service lines, and a right of entry to perform work deemed necessary.

#### ***6.2.2 Rebuttal of Control Presumption.***

Water systems are required to replace the entire LSL (up to the building inlet) unless they can successfully demonstrate to the State that part of the LSL is beyond their control. A water system can rebut the control presumption by citing local ordinances or State statutes, or in the case of private systems, the contract between the systems and their customers that limit the extent of control.

Systems that do not intend to replace the entire LSL are required to submit a letter to the State, within the first year of their replacement schedule, demonstrating that their control is limited. This letter must be accompanied by a copy of the legal

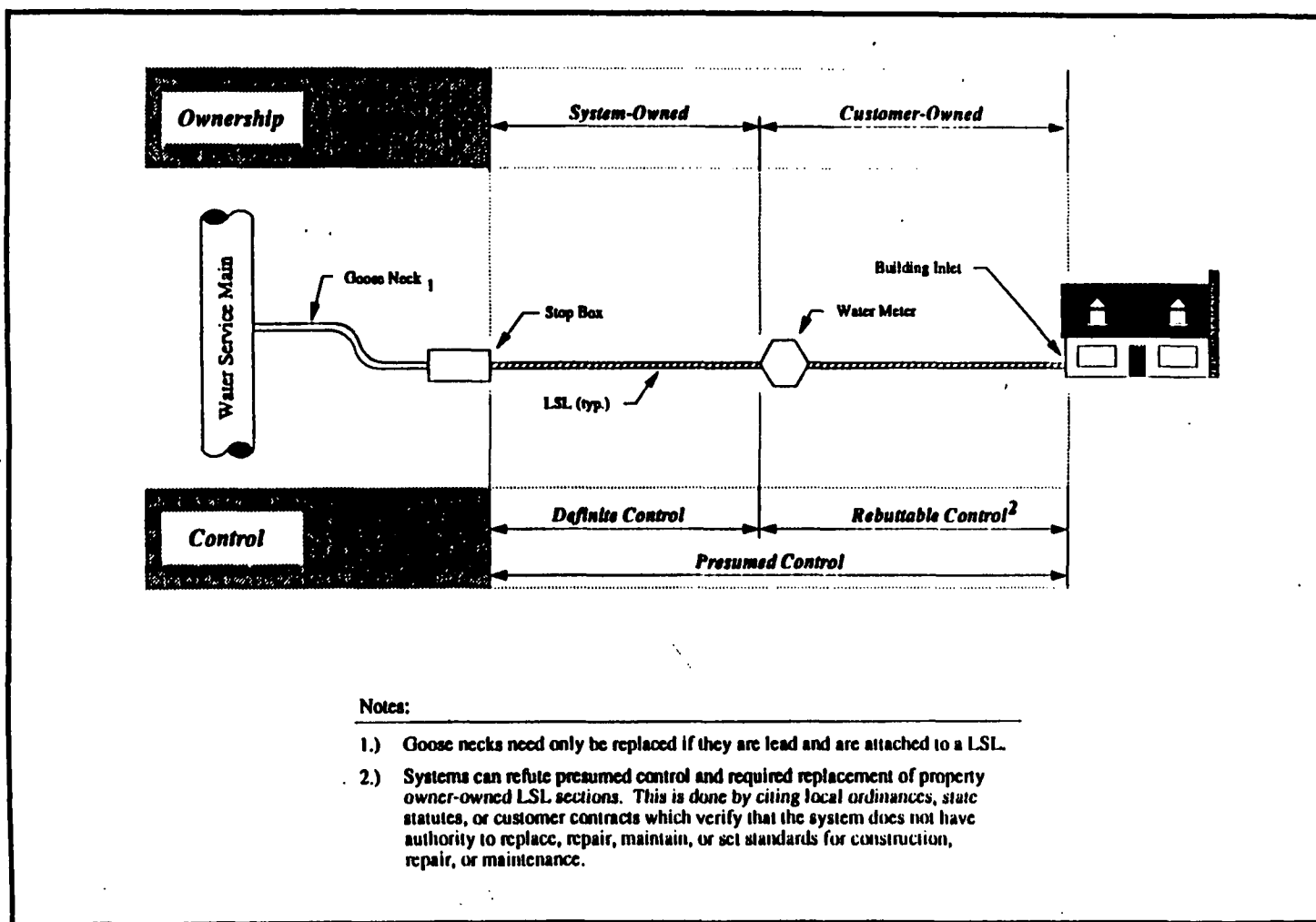


Figure 6-1. Extent of LSL Control



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authority the water system is relying upon to justify its position that the extent of its control is limited. On the basis of this legal authority, the State will determine whether the system correctly interprets its relevant legal authority.

EPA believes that requiring State review of PWS control presumption rebuttals is important to ensure that systems correctly apply the regulatory definition of control to their system. To expedite implementation of LSL replacement, States are not required to approve a system's interpretation of its legal authority prior to the system beginning LSL replacement. However, the State may determine that a system has incorrectly interpreted the extent of its control over LSLs. In all such instances, the State is required to explain the basis for its decision in writing and notify the system of that decision. The system must then replace the portion of the LSL under its control as determined by the State. Where a system's control does not extend over the entire LSL, the system is required to offer to replace the portion of the LSL controlled by the homeowner but is not required to bear the cost of replacing the building owner's portion of the line.

### ***6.2.3 Partial LSL Replacement.***

Systems replacing LSLs are required to replace the portions of the LSLs that are under their "control" as defined in §141.84(e) of the LCR and Section 6.2.1 of this manual. Control is often split between the PWS and the property owner. This potentially limits the PWS's ability to remove the entire LSL. The Rule requires that the system offer to replace

any portion of the LSL controlled by the homeowner but is not required to bear the cost of replacing the homeowner's portion.

Partial replacement of LSLs has been observed, in some cases, to result in short-term but significant increases in tap water lead levels (Hulsmann, 1990; Schock, 1990). EPA believes that such increases and associated health impacts will be minimized since effective corrosion control should be in place by that time, and also because customers will be informed of how they can minimize their exposure. The primary concern regarding lead in drinking water is not acute toxicity, but rather lead's capacity to accumulate in the body and result in chronic health effects. Thus, EPA believes that the potential risks posed by such temporary increases are outweighed by the importance of having lead levels reduced over the long term.

In those locations where only a portion of the LSL is replaced, PWSs must notify affected customers and offer them the option of having a follow-up tap sample collected and analyzed to determine whether there has been an increase in tap water lead levels. The PWS will not be required to pay for the collection or analysis of such samples nor will the system be required to collect and analyze the sample itself. However, if a customer accepts the offer, the PWS must report the sampling results to the customer within 14 days of partial replacement. The purpose of collecting the follow-up samples is to identify those locations where transient increases in water lead levels could occur and inform residents of the precautionary steps they should take (i.e., flushing water at the taps). Methods for collecting LSL samples at consumers' taps

are described in the LCR Guidance Manual, Volume 1 (Section 4.3).

### **6.3 Materials Evaluation**

A complete determination of all LSL sites may not have been accomplished during the Material Survey for the Sample Plan Development. This survey effort must be completed if a system is triggered into the LSLRP, because the initial number of LSLs determined serves as the basis for replacement rate determination. Methods for determining the locations of LSLs were presented in Section 3.0 of the Lead and Copper Rule Guidance Manual, Volume 1. Twelve months after a water system is triggered into the LSLRP, it is required to submit to the State a revised materials evaluation identifying the initial number of LSLs in its distribution system. The initial number of LSLs is the number of LSLs in place at the time the LSLRP begins.

EPA believes 12 months is an adequate period of time because water systems should have obtained such information either when they were required to determine whether their distribution system contained lead or copper pipes [§141.42(d)], or when they established their sampling pool for tap monitoring under this Rule. While some municipalities will undoubtedly have inadequate records documenting the location of its LSLs, most systems are not required to submit a complete material evaluation of LSLs to the State until 8 to 10 years after promulgation of the Rule. EPA believes this provides water systems with sufficient time to locate all LSLs and recommends that

systems with monitoring data indicating LSLs may be a problem begin identifying the location of LSLs now.

### **6.4 LSL Replacement and Schedule Requirements**

Systems which become subject to the LSLRP must physically replace all LSLs, except those for which the lead concentration in all lead service line samples is less than or equal to 0.015 mg/L. Thus, systems have a choice between replacing LSLs or conducting monitoring of the line to determine if the lead levels are less than or equal to 0.015 mg/L. LSLs may be considered to be "physically replaced", via the lead contribution presumption rebuttal and when excavation reveals that a presumed LSL is in fact not a LSL. Regardless of how LSLs are replaced/monitored, the process must proceed at the annual rate specified by the State and in accordance with size dependant LSLRP schedules. The following subsections discuss rebuttal of the lead contribution presumption, replacement/elimination rates, size-dependent LSLRP schedules, and LSLRP discontinuation.

#### **6.4.1 Rebuttal of Lead Contribution Presumption.**

The "lead contribution presumption" essentially presumes that each LSL scheduled for replacement significantly contributes to lead concentrations of more than 0.015 mg/L at the tap. Systems may rebut this presumption for individual LSLs, via sampling and analysis, if LSL samples (not

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first-draw) reveal that the lead concentrations are no more than 0.015 mg/L.

Detailed sampling procedures for LSL monitoring are provided in Chapter 4.0 of Volume I of the Lead and Copper Rule Guidance Manual; a general description is provided below. Each LSL sample must be one liter in volume and stand motionless in the LSL for at least six hours. LSL samples must be collected in one of the following ways:

1. Calculating the interior diameter and length of the pipe between the tap and the LSL, flushing the calculated volume of water, and collecting the next one liter of water; (Table 3-3 provides volumes of standing water for various pipe lengths and diameters);
2. Tapping directly into the LSL and collecting one liter of water from the line; or
3. Allowing the water to run until there is a change in temperature and collecting one liter of water immediately after the change takes place. This method may be used only when the sampling site is constructed as a single family residence.

If the concentration in the LSL sample is less than or equal to 0.015 mg/L, then the system need not replace the individual LSL. Furthermore, each of these LSLs may be counted as "replaced" in the LSLRP accounting system. LSL monitoring by PWSs is strictly optional. A water system may choose to replace LSLs without conducting any monitoring, regardless of actual lead contribution, or if lead levels in LSLs are expected to exceed 0.015 mg/L.

### ***6.4.2 Replacement/Elimination Rates.***

It is difficult to establish a replacement rate that can be applied nationwide because the number of LSLs in each system varies tremendously. EPA estimates that LSLs may comprise anywhere from 10 to 50 percent of the service lines in those systems that have LSLs. Replacement of all LSLs via normal maintenance schedules could take as long as 50 years for some systems. EPA believes that it is necessary to accelerate the rate at which LSLRP systems replace LSLs in order to ensure that public health will be adequately protected. States will be in the best position to assess the factual circumstances of each individual system and the schedule the system can feasibly meet.

EPA decided that in no case can a LSLRP system take more than 15 years to replace all its LSLs; where LSL "replacement" consists of the summation of the following:

- LSLs physically replaced;
- LSLs for which the "lead contribution presumption" is successfully rebutted via sampling and analysis; and
- Lines identified as LSLs in the materials evaluation which are found not to be LSLs upon excavation.

Therefore water systems subject to the LSLRP are required to annually "replace" at least 7 percent of their initial number of LSLs as identified in the materials evaluation (see Section 6.3). For example, a system that identifies 10,000 LSLs in its materials evaluation would be required to cumulatively account for replacement of at least 700 individual/additional LSLs each year via

physical LSL replacement, LSL lead contribution rebuttals, and/or when initially identified LSLs are found not to be LSLs upon excavation. The system's LSL replacement pool for a given year, for example, could potentially consist of 690 LSLs which are physically replaced, 8 LSL lead contribution rebuttals, and 2 via excavation. An LSL replacement work sheet, which could be used to assist systems in their LSLRP accounting process, and a completed example have been included as Tables 6-1 and 6-2, respectively.

The Rule also requires that water systems replace LSLs at a greater rate than 7 percent annually where the State finds that an accelerated schedule is feasible. The State must make such determinations in writing and must notify the system of its findings within six months after the system is triggered into the LSLRP.

### **6.4.3 Size-Dependent LSLRP Schedules.**

The timing of LSLRP requirements is dependent upon when systems complete corrosion control and/or source water treatment, which in turn varies based upon system size. This is particularly true for small and medium size systems based upon whether or not a corrosion control study is conducted. Schedules for small and medium-size systems, as well as large systems, are presented in Figure 6-2.

### **6.4.4 LSLRP Discontinuation.**

It is conceivable that systems can meet the lead AL which they had previously exceeded through improved treatment—corrosion control or source water treatment—or because they obtain an alternative source of water. Thus,

water systems can discontinue the LSLRP if they can demonstrate that first-draw tap water lead levels are below the lead AL for two consecutive six-month monitoring periods. EPA decided to require lead AL compliance over the course of an entire year to ensure that the lower levels genuinely reflect a lowering of lead levels, and not normal variability in lead levels at the tap. Recommencement of the replacement program is required if a system subsequently exceeds the lead AL during any single monitoring period.

## **6.5 Reporting Requirements**

Once the LSLRP is initiated, a system must meet reporting requirements in accordance with the standardized schedule presented in Table 6-3 and outlined below.

Within three months of being required to begin the LSLRP, a system seeking to rebut the control presumption (presumes the system controls the entire LSL) must submit a letter to the State describing the legal authority which limits the system's control over the LSL and explain the extent of the system's control. The letter must include copies of the State statute, municipal ordinance, public service contract, or any other legal authority the system contends limits control.

Within 12 months a system must submit to the State a schedule for the replacement of all its LSLs at the annual rate approved by the State. The schedule must also state the initial number of LSLs. The schedule could include the location of the LSLs within the distribution system, and identify the LSLs scheduled for replacement during each year of the replacement schedule.

Every 12 months a system must demonstrate that 7 percent (or more as specified by the State) of its LSLs have

**Table 6-1. LSLRP General Accounting Worksheet**

Initial No. of LSLs: \_\_\_\_\_

Required Annual Replacement (No.): \_\_\_\_\_

Required Annual Replacement (%): \_\_\_\_\_

Year	Annual Numbers					Cumulative Numbers	
	PHS	RBT	EXC	No.REP	%REP	CNo.REP	C%REP
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							

- PHS = Number of LSLs physically replaced in the given year.  
 RBT = Number of LSLs eliminated via Pb contribution rebuttals.  
 EXC = Number of initially identified LSLs which are found not to be LSLs upon excavation for given year.  
 No.REP = Number of LSLs "replaced" in the given year (PHS + RBT + EXC).  
 %REP = Percent of LSLs replaced for the given year (No.Rep/Initial No.)(100)  
 CNo.REP = Cumulative number of LSLs replaced through given year.  
 C%REP = Cumulative percent of LSLs replaced through given year.

**Table 6-2. LSLRP General Accounting Worksheet**

Initial No. of LSLs: \_\_\_\_\_

Required Annual Replacement (No.): \_\_\_\_\_

Required Annual Replacement (%): \_\_\_\_\_

Year	Annual Numbers					Cumulative Numbers	
	PHS	RBT	EXC	No.REP	%REP	CNo.REP	C%REP
1	693	7	0	700	7	700	7
2	694	6	0	700	7	1400	14
3	690	10	0	700	7	2100	21
4	690	10	0	700	7	2800	28
5	690	10	0	700	7	3500	35
6	690	10	0	700	7	4200	42
7	688	12	0	700	7	4900	49
8	689	11	0	700	7	5600	56
9	670	29	1	700	7	6300	63
10	664	34	2	700	7	7000	70
11	665	34	1	700	7	7700	77
12	645	55	0	700	7	8400	84
13	638	60	2	700	7	9100	91
14	630	68	2	700	7	9800	98
15	186	12	2	200	2	10000	100

PHS = Number of LSLs physically replaced in the given year.

RBT = Number of LSLs eliminated via Pb contribution rebuttals.

EXC = Number of initially identified LSLs which are found not to be LSLs upon excavation for given year.

No.REP = Number of LSLs "replaced" in the given year (PHS + RBT + EXC).

%REP = Percent of LSLs replaced for the given year (No.Rep/Initial No.)(100)

CNo.REP = Cumulative number of LSLs replaced through given year.

C%REP = Cumulative percent of LSLs replaced through given year.

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**NOTE:** Figure 6-2 is a large fold-out sheet. Use this page number.

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**Table 6-3. Reporting Requirements Schedule**

Within 3 Mo of LSLRP Triggering	Within 12 Mo of LSLRP Triggering	Within Each 12 Mo Period Following LSLRP Triggering
Rebuttal of "control presumption"	Materials evaluation and replacement schedule	Certification of "replacement" of LSLs equaling at least 7 percent of the initial number of LSLs as specified by the State

been replaced. Sample documentation demonstrating rebuttal of the lead contribution presumption must also be submitted in accordance with this schedule. The annual letter must contain the following information:

1. The number of LSLs scheduled to be replaced during the previous year of the replacement schedule.
2. The number and location of each LSL replaced during the previous year of the schedule.
3. If measured, the water lead concentration and location of each LSL sampled, the sampling method, and the date of sampling.

EPA believes that this information must be submitted annually to insure that the system is properly completing the LSLRP.

### **6.6 Record-Keeping Requirements**

Any system subject to the record-keeping requirements of §141.91 must retain on its premises original records of all sampling data and analyses, reports, surveys, letters, evaluations, schedules, State determinations, and any other information required by §141.81 through §141.88. Each water system shall retain these records for no fewer than 12 years.

### **6.7 References**

Hulsmann, A.D. 1990. Particulate Lead in Water Supplies. *Jour. Institution of Water and Envir. Mang.* 4(1):19-25.

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## Appendix A

### ***Corrosion Indices for the Precipitation of Protective Coatings***

Many corrosion control programs for water utilities have targeted the protection of metal pipes through precipitation of calcium carbonate ( $\text{CaCO}_3$ ). This process depends on the equilibrium reactions involving the calcium ion ( $\text{Ca}^{2+}$ ), hydrogen ion ( $\text{H}^+$ ), hydroxide ion ( $\text{OH}^-$ ), carbonic acid ( $\text{H}_2\text{CO}_3^*$ ), carbon dioxide ( $\text{CO}_2$ ), bicarbonate ion ( $\text{HCO}_3^-$ ), and carbonate ion ( $\text{CO}_3^{2-}$ ). The objective of the process is to produce a finished water which will evenly precipitate calcium carbonate on the pipe walls within the distribution system. This means that the finished water should be supersaturated with respect to calcium carbonate to the extent that precipitation occurs.

A multitude of corrosion indices have been developed over the years to describe the precipitation of calcium carbonate. The recommended index is the Calcium Carbonate Precipitation Potential (CCPP) for use in evaluating the water quality goals necessary to successfully provide corrosion control protection through the formation of calcium carbonate films. The Langelier Saturation Index (LI) may also be used by PWSs due to its long history of application and the ability of some systems to develop reliable relationships between LI and corrosion control protection. Other corrosion indices are not recommended for determining

water quality goals generating calcium carbonate precipitation in distribution and home plumbing systems.

### ***Calcium Carbonate Precipitation Potential.***

The term calcium carbonate precipitation potential (CCPP) refers to the theoretical quantity of calcium carbonate that can be precipitated from waters that are super-saturated. A treated water CCPP of 4-10 mg/l (as  $\text{CaCO}_3$ ) is typically required to promote formation of protective calcium carbonate deposits. For large systems, higher CCPPs may be required to ensure maintenance of calcium carbonate deposits throughout the distribution system.

CCPP has also been shown to relate directly to reaction kinetics as found by Nancollas and Reddy (1976) and presented by Rossum and Merrill (1983):

$$d[\text{Ca}^{2+}]/dt = -10^{-5} KS(\text{CCPP})^2$$

where K is the rate constant for crystalline growth and S is the surface area available for precipitation of a given particle size. When applying corrosion indices as a surrogate measure of corrosion control performance, it is important that the application be supported by additional information, such as distribution system monitoring, in-situ coupon testing, bench-scale corrosion testing, and inspection of pipe materials removed from the distribution system during maintenance and repair.

## ***Determining the Calcium Carbonate Precipitation Potential***

CCPP can be determined graphically through use of Caldwell-Lawrence diagrams, analytically through equilibrium equations, or by computer analysis.

$$\text{CCPP} = 50,000 * ([\text{Alk}]_i - [\text{Alk}]_{\text{eq}})$$

Theoretical basis for determining the amount of  $\text{CaCO}_3$  precipitated or dissolved by waters depending on their saturation condition as presented by Merrill and Sanks (1977a, 1977b, 1978).

CCPP = 0:  $\text{CaCO}_3$  saturated solution.

CCPP > 0:  $\text{CaCO}_3$  supersaturated solution, and the CCPP value denotes the milligrams per liter of  $\text{CaCO}_3$  which will be precipitated.

CCPP < 0:  $\text{CaCO}_3$  undersaturated solution, and the CCPP value denotes the milligrams per liter of  $\text{CaCO}_3$  needed to be dissolved into solution to bring to saturation.

Rule of Thumb Goal: 4-10 mg/L  $\text{CaCO}_3$

### ***CCPP Calculation Procedures:***

#### **A. Definition of Terms and Values of Constants**

$[\text{Alk}]_i$  Measured value of alkalinity in the finished water,

representing the alkalinity of solution prior to precipitation of calcium carbonate.

$[\text{Alk}]_{\text{eq}}$  Equilibrium alkalinity resulting after precipitation of the calcium carbonate content beyond saturation. Calculation of this term requires an iterative solution for the hydrogen ion concentration at equilibrium. Once this is done,  $[\text{Alk}]_{\text{eq}}$  can be calculated as follows:

$$[\text{Alk}]_{\text{eq}} = t_{\text{eq}}/p_{\text{eq}} * (\text{Acy}_i - s_{\text{eq}}) - s_{\text{eq}}$$

$$\text{where } t_{\text{eq}} = (2K_2' + [\text{H}^+]_{\text{eq}})/[\text{H}^+]_{\text{eq}}$$

$$p_{\text{eq}} = (2[\text{H}^+]_{\text{eq}} + K_1')/K_1'$$

$$s_{\text{eq}} = [\text{H}^+]_{\text{eq}} - K_w'/[\text{H}^+]_{\text{eq}}$$

and,

$K_H$  = Henry's law constant for  $\text{CO}_2$

$K_w$  = dissociation constant for water

$K_1'$  = first dissociation constant of carbonic acid.

$K_2'$  = second dissociation constant of carbonic acid

$[\text{Acy}]_i$  = Acidity of the finished water.

$$= C_T * (a_1 + 2 * a_0) + [\text{H}^+] - [\text{OH}^-]$$

$$a_1 = ([\text{H}^+]/K_1' + 1 + K_2'/[\text{H}^+])^{-1}$$

$$a_0 = (1 + K_1'/[\text{H}^+] + K_1' * K_2'/[\text{H}^+])^{-1}$$

The equilibrium constants used in the above equations are given in Table A-1 for various temperature conditions.

**Table A-1. Equilibrium Constants for Carbonate-Water System**

Temp °C	pK <sub>sp</sub> <sup>1</sup>	pK <sub>w</sub>	pK <sub>H</sub>	pK <sub>1</sub> '	pK <sub>2</sub> '
0	8.03	14.93	1.11	6.579	10.625
5	8.09	14.73	1.19	6.517	10.557
10	8.15	14.53	1.27	6.464	10.490
15	8.21	14.35	1.32	6.419	10.430
20	8.27	14.17	1.41	6.381	10.377
25	8.33	14.00	1.47	6.352	10.329
30	8.38	13.83	1.53	6.327	10.290
<sup>1</sup> Derived from equation, $pK_{sp} = 0.01183 \cdot (\text{Temp}) + 8.03$ , Larson and Boswell, 1942.					

### B. Algorithm for Iterative Solution

The CCPP represents in mg/L as CaCO<sub>3</sub> the saturation state of calcium carbonate with respect to existing conditions (Alk<sub>i</sub>) and the equilibrium conditions which would exist after the water's potential to precipitate or dissolve calcium carbonate had occurred (Alk<sub>eq</sub>). During this process, the equivalents of calcium precipitated (or dissolved) must be equal to the equivalents of alkalinity precipitated (or dissolved). However, the acidity of the water remains constant and therefore can be used to determine the equilibrium alkalinity conditions as described below.

$$\text{Acy}_i = \text{Acy}_{eq} = [(\text{Alk}_i + s_i)/t_i] \cdot p_i + s_i$$

where  $s_i$ ,  $t_i$ , and  $p_i$  are defined as follows:

$$\begin{aligned} s_i &= [\text{H}^+] - K_w/[\text{H}^+] \\ t_i &= (2 \cdot K_2' + [\text{H}^+])/[\text{H}^+] \\ p_i &= (2 \cdot [\text{H}^+] + K_1')/K_1' \end{aligned}$$

Since acidity remains conservative through the precipitation/dissolution of calcium carbonate, the actual acidity of the water (Acy<sub>i</sub>) may be used to define the

equilibrium alkalinity (Alk<sub>eq</sub>) as shown below:

$$\text{Alk}_{eq} = t_{eq}/p_{eq} \cdot (\text{Acy}_i - s_{eq}) - s_{eq}$$

The equilibrium alkalinity condition may also be related to the initial calcium and alkalinity through the following equation:

$$\begin{aligned} 2 \cdot [\text{Ca}^{2+}]_i - \text{Alk}_i &= \\ 2 \cdot K_{sp}' \cdot r_{eq} / (\text{Alk}_{eq} + s_{eq}) - \text{Alk}_{eq} \end{aligned}$$

$$\text{with } r_{eq} = ([\text{H}^+]_{eq} + 2 \cdot K_2')/K_2'$$

Substituting  $\text{Alk}_{eq} = f(\text{Acy}_i)$  into the above equation yields the relationship below:

$$\begin{aligned} 2 \cdot [\text{Ca}^{2+}]_i - \text{Alk}_i &= \\ [(2 \cdot K_{sp}' \cdot r_{eq} \cdot p_{eq}) / (t_{eq} \cdot (\text{Acy}_i - s_{eq}))] - & \\ [t_{eq} \cdot (\text{Acy}_i - s_{eq}) / p_{eq}] + s_{eq} \end{aligned}$$

If we let TERM0 equal the left side of the above equation, and TERM1 and TERM2 equal the first two terms on the right side of the above equation, then this reduces to:

$$\text{TERM0} = \text{TERM1} - \text{TERM2} + s_{eq}$$

To solve for the equilibrium terms, H<sub>eq</sub> is assigned a value initially. The above equation is tested to determine whether the

assigned value satisfies the conditions (i.e., does  $TERM0 = TERM1 - TERM2 + s_{eq}?$ ). If not, then iterate the process by assigning a new value for  $H_{eq}$  until an adequate degree of accuracy is reached. In the following examples, this method of solving for CCPP was used with a tolerance of 0.001 for the above equation.

Spreadsheet formats are provided to assist in the design and development of a CCPP calculation tool.

### **C. Finding the CCPP Value for a Specific Water Quality Condition**

A PWS performing lime softening has a finished water with the following characteristics: pH = 8.6; alkalinity = 90 mg/L as  $CaCO_3$ ; and calcium hardness = 100 mg/L as  $CaCO_3$ . The worksheet presented on the following page (Exhibit A-1) calculates the CCPP (6.6 mg/L as  $CaCO_3$ ) for this supply using the iterative solution discussed above.

### **D. Finding the Water Quality Conditions for a Desired CCPP.**

To achieve a desired CCPP, any one or more of the three key water quality parameters may be modified. Exhibits A-2 and A-3 demonstrate this by modifying pH and alkalinity, respectively, to achieve a desired CCPP of 8.0 mg/L as  $CaCO_3$  for the same water described above (Part B). When pH and calcium held constant, the required alkalinity is 101.8 mg/L as  $CaCO_3$  for the targeted CCPP; with alkalinity and calcium contents are held constant, the resultant pH of 8.8 is required to achieve the desired CCPP.

**Langelier Saturation Index.** A commonly used measure of a water's

ability to deposit calcium carbonate is Langelier's Saturation Index (LI). This value is determined by subtracting the pH of saturation (known as  $pH_s$ , and dependent upon the calcium ion concentration, alkalinity, temperature, and dissolved solids concentration of the water) from the actual pH ( $pHa$ ).

A negative LI value indicates under-saturation and a tendency for the water to dissolve calcium carbonate. A positive value indicates supersaturation and a tendency for the water to deposit calcium carbonate. A value of zero indicates that the water is in chemical balance with respect to calcium carbonate.

While the LI is widely used, it has several notable shortcomings. Due to its qualitative nature, it indicates only the tendency or direction of calcium carbonate precipitation. It cannot predict the actual precipitation potential, or the amount of excess calcium carbonate available for precipitation.

For example, it has often been found that although a positive LI was maintained, severe corrosion had occurred in the distribution system, and inspections of pipe and fittings revealed no evidence of a coating of calcium carbonate. In other situations, however, PWSs have had limited corrosion problems with slightly negative LIs. In these instances, the amount of alkalinity may have been sufficient for carbonate passivation to reduce corrosion activity. In practice, the appropriate LI for a given system is highly site-specific, and is dependent upon treated water composition and distribution system size and complexity.

**Langelier Index (LI) = pH - pH<sub>s</sub>**

**Developed by W.F. Langelier  
(1936)**

**LI = 0: CaCO<sub>3</sub> saturation**

**LI > 0: CaCO<sub>3</sub> supersaturation**

**LI < 0: CaCO<sub>3</sub> undersaturation**

**Rule of Thumb Goal: +0.8 - +1.0**

## **Calculation Procedure**

### **A. Definition of Terms**

pH<sub>s</sub> Saturation pH for calcium carbonate calculated as follows:

$$\text{pH}_s = -\log_{10} [\text{H}^+] - \log_{10} f_m$$
$$[\text{H}^+] = (-B \pm \sqrt{B^2 - 4AC})/2A$$

where:

$$A = 1 - [\text{Ca}^{2+}]K_2'/K_s'$$

$$B = K_2'(2 - [\text{Ca}^{2+}][\text{Alk}]/K_s')$$

$$C = K_w'K_2'[\text{Ca}_{2+}]/K_s'$$

and,

K<sub>w</sub>' = Dissociation constant for water

K<sub>s</sub>' = Solubility product constant for calcium carbonate.

K<sub>2</sub>' = Second dissociation constant for carbonic acid.

f<sub>m</sub> = activity coefficient for the monovalent ions. This term is normally neglected in calculating LI.

**Conversion Between Total Alkalinity and Dissolved Inorganic Carbonate.** To more easily utilize the solubility contour diagrams presented in Chapter 2.0 of this volume, Table A-2 provides a conversion chart for total alkalinity (Talk) and dissolved inorganic carbonate (DIC) by water temperature and pH. To use Table A-2, a PWS with a known Talk (expressed as mg CaCO<sub>3</sub>/L), pH, and water temperature, find the factors A and B corresponding to their conditions. The

equivalent DIC level for that water supply can be calculated as follows:

$$\text{DIC (mg CaCO}_3\text{/L)} = [(\text{Talk}/50,000) + A] \times B$$

The resulting DIC can be used in finding the lead or copper solubility for the defined condition per Figures 2-2, 2-3, and 2-5 in this volume.

## **References**

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## Exhibit A-1. CCCP Calculation Procedures

### Example 1 – Spreadsheet for Calculating CCCP

Determine CCCP

Given: pH=8.6  
Alk=90 mg/l as CaCO<sub>3</sub>  
Cal=100 mg/l as CaCO<sub>3</sub>  
Temp=20 C

NO	Variable	Definition	Comments	Input	Output
1	Ca	= Calcium, moles/l (1)	given	1.0E-03	
2	Alki	= Alkalinity, equiv/l (1)	given	1.8E-03	
3	Hi	= Hydrogen Ion, moles/l (1)	given	2.5E-09	
4	K'sp	= Solubility Constant, CaCO <sub>3</sub>	Table 2	5.4E-09	
5	K'w	= Dissociation Constant for Water	Table 2	6.8E-15	
6	K'1	= 1st Carbonic Dissociation Constant	Table 2	4.2E-07	
7	K'2	= 2nd Carbonic Dissociation Constant	Table 2	4.2E-11	
8	Req	= (Heq - 2*K'2)/K'2	calculated		3.0E+02
9	Peq	= (2*Heq + K'1)/K'1	calculated		1.1E+00
10	Teq	= (2*K'2 + Heq)/Heq	calculated		1.0E+00
11	Seq	= Heq - K'w/Heq	calculated		-5.2E-07
12	Pi	= (2*Hi + K'1)/K'1	calculated		1.0E+00
13	Si	= Hi - K'w/Hi	calculated		-2.7E-06
14	Ti	= (2*K'2 + Hi)/Hi	calculated		1.0E+00
15	Acyi	= ((Alki + Si)/Ti)*Pi + Si	calculated		1.8E-03
16	Alkeq	= Teq/Peq*(Acyi-Seq) - Seq, mg/l(3)	calculated		83.4
17	Term1	= 2*K'sp*Req*Peq/T/(Acyi - Seq)	calculated		1.9E-03
18	Term2	= (Acyi - Seq)*Teq/Peq	calculated		1.7E-03
19	Heq	= Equilibrium H, moles/l (2)	iterate	1.3E-08	
20	Term0	= 2*Ca - Alki	calculated		2.0E-04
21	Right	= Term1 - Term2 + Seq	calculated		2.0E-04
22	CCCP	= Alki - Alkeq, mg/l as CaCO <sub>3</sub> (3)	calculated		6.6

- (1) Convert given information into proper units of moles/l and equiv/l.
- (2) Iteration can be accomplished by several procedures. Manual iteration requires the user to input various values of Heq until rows 20 and 21 converge. Another option in spreadsheets such as Lotus 123 and Microsoft Excel, allow cells to be "dependant" on one another. In this case rows 20 and 21 could be equated and the recalculate key used to iterate. Macros could also be written that would iterate using a loop command.
- (3) Covert to mg/l by multiplying by 50,000.

## Exhibit A-3. CCCP Calculation Procedures

### Example 3 – Spreadsheet for Calculating pH for Given CCPP

		Determine pH (Based on information from Example 1)	Given:	CCPP=8 mg/l Alk=90 mg/l as CaCO <sub>3</sub> Cal=100 mg/l as CaCO <sub>3</sub> Temp=20 C		
NO	Variable	Definition		Comments	Input	Output
1	Hi	Hydrogen Ion, moles/l	(1) (2)	vary	1.8E-09	
2	Ca	Calcium, moles/l	(1)	given	1.0E-03	
3	Alki	Alkalinity, equiv/l	(1)	given	1.8E-03	
4	K'sp	Solubility Constant, CaCO <sub>3</sub>		Table 2	5.4E-09	
5	K'w	Dissociation Constant for Water		Table 2	6.8E-15	
6	K'1	1st Carbonic Dissociation Constant		Table 2	4.2E-07	
7	K'2	2nd Carbonic Dissociation Constant		Table 2	4.2E-11	
8	Req	$(\text{Heq} - 2 \cdot \text{K}'2) / \text{K}'2$		calculated		2.9E+02
9	Peq	$(2 \cdot \text{Heq} + \text{K}'1) / \text{K}'1$		calculated		1.1E+00
10	Teq	$(2 \cdot \text{K}'2 + \text{Heq}) / \text{Heq}$		calculated		1.0E+00
11	Seq	$\text{Heq} - \text{K}'w / \text{Heq}$		calculated		-5.3E-07
12	Pi	$(2 \cdot \text{Hi} + \text{K}'1) / \text{K}'1$		calculated		1.0E+00
13	Si	$\text{Hi} - \text{K}'w / \text{Hi}$		calculated		-3.8E-06
14	Ti	$(2 \cdot \text{K}'2 + \text{Hi}) / \text{Hi}$		calculated		1.0E+00
15	Acyi	$((\text{Alki} + \text{Si}) / \text{Ti}) \cdot \text{Pi} + \text{Si}$		calculated		1.7E-03
16	Alkeq	$\text{Teq} / \text{Peq} \cdot (\text{Acyi} - \text{Seq}) - \text{Seq}$ , mg/l(4)		calculated		82.0
17	Term1	$2 \cdot \text{K}'sp \cdot \text{Req} \cdot \text{Peq} / \text{T} / (\text{Acyi} - \text{Seq})$		calculated		1.8E-03
18	Term2	$(\text{Acyi} - \text{Seq}) \cdot \text{Teq} / \text{Peq}$		calculated		1.6E-03
19	Heq	Equilibrium H, moles/l	(3)	iterate	1.2E-08	
20	Term0	$2 \cdot \text{Ca} - \text{Alki}$		calculated		2.0E-04
21	Right	$\text{Term1} - \text{Term2} + \text{Seq}$		calculated		2.0E-04
22	CCPP	$\text{Alki} - \text{Alkeq}$ , mg/l	(4)	calculated		8.0
23	pH	$\text{pHi}, -\log \text{Hi}$		calculated		8.8

- (1) Convert given information into proper units of moles/l and equiv/l.
- (2) Enter in values for Hi (moles/l) and then iterate Heq as in Example 1. Continue this process until CCPP converges to the targeted goal value (8 mg/l for Example 3).
- (3) Iteration can be accomplished by several procedures. Manual iteration requires the user to input various values of Heq until rows 20 and 21 converge. Another option in spreadsheets such as Lotus 123 and Microsoft Excel, allow cells to be "dependant" on one another. In this case rows 20 and 21 could be equated and the recalculate key used to iterate. Macros could also be written that would iterate using a loop command.
- (4) Covert to mg/l by multiplying by 50,000.

## Exhibit A-2. CCCP Calculation Procedures

### Example 2 – Spreadsheet for Calculating Alkalinity for Given CCCP

Determine Alkalinity (Based on information from Example 1)			Given: CCCP=8 mg/l pH=8.6 Cal=100 mg/l as CaCO <sub>3</sub> Temp=20 C		
NO	Variable	Definition	Comments	Input	Output
1	Alki = Alkalinity, equiv/l	(1) (2)	vary	2.0E-03	
2	Ca = Calcium, moles/l	(1)	given	1.0E-03	
3	Hi = Hydrogen Ion, moles/l	(1)	given	2.5E-09	
4	K'sp = Solubility Constant, CaCO <sub>3</sub>		Table 2	5.4E-09	
5	K'w = Dissociation Constant for Water		Table 2	6.8E-15	
6	K'1 = 1st Carbonic Dissociation Constant		Table 2	4.2E-07	
7	K'2 = 2nd Carbonic Dissociation Constant		Table 2	4.2E-11	
8	Req = (Heq - 2*K'2)/K'2		calculated		3.3E+02
9	Peq = (2*Heq + K'1)/K'1		calculated		1.1E+00
10	Teq = (2*K'2 + Heq)/Heq		calculated		1.0E+00
11	Seq = Heq - K'w/Heq		calculated		-4.7E-07
12	Pi = (2*Hi + K'1)/K'1		calculated		1.0E+00
13	Si = Hi - K'w/Hi		calculated		-2.7E-06
14	Ti = (2*K'2 + Hi)/Hi		calculated		1.0E+00
15	Acyi = ((Alki + Si)/Ti)*Pi + Si		calculated		2.0E-03
16	Term1 = 2*K'sp*Req*Peq/T/(Acyi - Seq)		calculated		1.8E-03
17	Term2 = (Acyi - Seq)*Teq/Peq		calculated		1.9E-03
18	Alkeq = Teq/Peq*(Acyi-Seq) - Seq, mg/(4)		calculated		93.7
19	Heq = Equilibrium H, moles/l	(3)	iterate	1.4E-08	
20	Term0 = 2*Ca - Alki		calculated		-3.5E-05
21	Right = Term1 - Term2 + Seq		calculated		-3.5E-05
22	CCCP = Alk - Alkf, mg/l	(4)	calculated		8.0
23	Alki = Alkalinity, mg/l as CaCO <sub>3</sub>	(4)	calculated		101.8

- (1) Convert given information into proper units of moles/l and equiv/l.
- (2) Enter in values for alkalinity (moles/l) and then iterate Heq as in Example 1. Continue this process until CCCP converges to the targeted goal value (8 mg/l for Example 2).
- (3) Iteration can be accomplished by several procedures. Manual iteration requires the user to input various values of Heq until rows 20 and 21 converge. Another option in spreadsheets such as Lotus 123 and Microsoft Excel, allow cells to be "dependant" on one another. In this case rows 20 and 21 could be equated and the recalculate key used to iterate. Macros could also be written that would iterate using a loop command.
- (4) Covert to mg/l by multiplying by 50,000.



Table A-2

Total Alkalinity (TALK) to Dissolved Inorganic Carbonate (DIC) Conversion Variables

Determine A &amp; B via the below table. Then compute DIC as follows:

DIC as ppm CaCO<sub>3</sub> = [(TALK in ppm CaCO<sub>3</sub>/50,000) + A] \* B

pH	T=0 (deg. C)		T=5 (deg. C)		T=10 (deg. C)		T=15 (deg. C)		T=20 (deg. C)		T=25 (deg. C)	
	A	B	A	B	A	B	A	B	A	B	A	B
6.0	9.99E-07	2.40E+05	9.98E-07	2.14E+05	9.97E-07	1.96E+05	9.96E-07	1.81E+05	9.93E-07	1.70E+05	9.90E-07	1.62E+05
6.1	7.93E-07	2.01E+05	7.92E-07	1.81E+05	7.91E-07	1.66E+05	7.89E-07	1.54E+05	7.86E-07	1.45E+05	7.82E-07	1.39E+05
6.2	6.29E-07	1.70E+05	6.28E-07	1.54E+05	6.26E-07	1.42E+05	6.24E-07	1.33E+05	6.20E-07	1.26E+05	6.15E-07	1.21E+05
6.3	4.99E-07	1.45E+05	4.97E-07	1.32E+05	4.95E-07	1.23E+05	4.92E-07	1.16E+05	4.88E-07	1.10E+05	4.81E-07	1.06E+05
6.4	3.95E-07	1.25E+05	3.93E-07	1.15E+05	3.91E-07	1.08E+05	3.87E-07	1.02E+05	3.81E-07	9.78E+04	3.73E-07	9.48E+04
6.5	3.13E-07	1.10E+05	3.10E-07	1.02E+05	3.07E-07	9.60E+04	3.02E-07	9.15E+04	2.95E-07	8.80E+04	2.85E-07	8.55E+04
6.6	2.47E-07	9.76E+04	2.44E-07	9.13E+04	2.39E-07	8.65E+04	2.33E-07	8.29E+04	2.24E-07	8.02E+04	2.11E-07	7.82E+04
6.7	1.94E-07	8.78E+04	1.90E-07	8.28E+04	1.85E-07	7.90E+04	1.77E-07	7.62E+04	1.66E-07	7.40E+04	1.49E-07	7.24E+04
6.8	1.51E-07	8.00E+04	1.47E-07	7.60E+04	1.40E-07	7.30E+04	1.30E-07	7.08E+04	1.16E-07	6.90E+04	9.54E-08	6.78E+04
6.9	1.17E-07	7.39E+04	1.11E-07	7.07E+04	1.02E-07	6.83E+04	9.04E-08	6.65E+04	7.22E-08	6.51E+04	4.65E-08	6.41E+04
7.0	8.83E-08	6.89E+04	8.14E-08	6.64E+04	7.05E-08	6.45E+04	5.53E-08	6.31E+04	3.24E-08	6.20E+04	1.53E-08	6.12E+04
7.1	6.46E-08	6.50E+04	5.60E-08	6.30E+04	4.23E-08	6.15E+04	2.32E-08	6.04E+04	-5.68E-09	5.95E+04	-4.65E-08	5.89E+04
7.2	4.45E-08	6.19E+04	3.36E-08	6.03E+04	1.63E-08	5.91E+04	-7.70E-09	5.82E+04	-4.41E-08	5.75E+04	-9.54E-08	5.70E+04
7.3	2.67E-08	5.95E+04	1.30E-08	5.82E+04	-8.77E-09	5.73E+04	-3.90E-08	5.65E+04	-8.48E-08	5.60E+04	-1.49E-07	5.56E+04
7.4	1.03E-08	5.75E+04	-6.96E-09	5.65E+04	-3.43E-08	5.57E+04	-7.24E-08	5.52E+04	-1.30E-07	5.47E+04	-2.11E-07	5.44E+04
7.5	-5.53E-09	5.60E+04	-2.73E-08	5.51E+04	-6.17E-08	5.45E+04	-1.10E-07	5.41E+04	-1.82E-07	5.37E+04	-2.85E-07	5.35E+04
7.6	-2.17E-08	5.47E+04	-4.90E-08	5.41E+04	-9.24E-08	5.36E+04	-1.53E-07	5.32E+04	-2.44E-07	5.29E+04	-3.73E-07	5.27E+04
7.7	-3.89E-08	5.37E+04	-7.34E-08	5.32E+04	-1.28E-07	5.28E+04	-2.04E-07	5.25E+04	-3.19E-07	5.23E+04	-4.81E-07	5.21E+04
7.8	-5.83E-08	5.29E+04	-1.02E-07	5.25E+04	-1.70E-07	5.22E+04	-2.66E-07	5.20E+04	-4.11E-07	5.18E+04	-6.15E-07	5.16E+04
7.9	-8.07E-08	5.23E+04	-1.35E-07	5.20E+04	-2.22E-07	5.17E+04	-3.42E-07	5.15E+04	-5.24E-07	5.13E+04	-7.82E-07	5.12E+04
8.0	-1.07E-07	5.18E+04	-1.76E-07	5.15E+04	-2.85E-07	5.13E+04	-4.37E-07	5.11E+04	-6.66E-07	5.10E+04	-9.90E-07	5.09E+04
8.1	-1.40E-07	5.13E+04	-2.26E-07	5.11E+04	-3.64E-07	5.09E+04	-5.54E-07	5.08E+04	-8.43E-07	5.07E+04	-1.25E-06	5.06E+04
8.2	-1.80E-07	5.10E+04	-2.89E-07	5.08E+04	-4.61E-07	5.07E+04	-7.02E-07	5.05E+04	-1.07E-06	5.04E+04	-1.58E-06	5.03E+04
8.3	-2.29E-07	5.07E+04	-3.67E-07	5.05E+04	-5.84E-07	5.04E+04	-8.86E-07	5.03E+04	-1.34E-06	5.02E+04	-1.99E-06	5.01E+04
8.4	-2.91E-07	5.05E+04	-4.64E-07	5.03E+04	-7.37E-07	5.02E+04	-1.12E-06	5.01E+04	-1.69E-06	5.00E+04	-2.51E-06	4.99E+04
8.5	-3.68E-07	5.02E+04	-5.86E-07	5.01E+04	-9.30E-07	4.99E+04	-1.41E-06	4.98E+04	-2.13E-06	4.97E+04	-3.16E-06	4.96E+04
8.6	-4.65E-07	5.00E+04	-7.39E-07	4.99E+04	-1.17E-06	4.97E+04	-1.78E-06	4.96E+04	-2.69E-06	4.95E+04	-3.98E-06	4.94E+04
8.7	-5.87E-07	4.98E+04	-9.31E-07	4.96E+04	-1.48E-06	4.95E+04	-2.24E-06	4.94E+04	-3.39E-06	4.92E+04	-5.01E-06	4.91E+04
8.8	-7.40E-07	4.96E+04	-1.17E-06	4.94E+04	-1.86E-06	4.92E+04	-2.82E-06	4.91E+04	-4.26E-06	4.89E+04	-6.31E-06	4.88E+04
8.9	-9.32E-07	4.93E+04	-1.48E-06	4.91E+04	-2.34E-06	4.90E+04	-3.55E-06	4.88E+04	-5.37E-06	4.86E+04	-7.94E-06	4.84E+04

Table A-2

## Total Alkalinity (TALK) to Dissolved Inorganic Carbonate (DIC) Conversion Variables

Determine A &amp; B via the below table. Then compute DIC as follows:

$$\text{DIC as ppm CaCO}_3 = [(\text{TALK in ppm CaCO}_3/50,000) + A] \cdot B$$

pH	T=0 (deg. C)		T=5 (deg. C)		T=10 (deg. C)		T=15 (deg. C)		T=20 (deg. C)		T=25 (deg. C)	
	A	B	A	B	A	B	A	B	A	B	A	B
9.0	-1.17E-06	4.90E+04	-1.86E-06	4.88E+04	-2.95E-06	4.86E+04	-4.47E-06	4.84E+04	-6.76E-06	4.82E+04	-1.00E-05	4.80E+04
9.1	-1.48E-06	4.87E+04	-2.34E-06	4.85E+04	-3.71E-06	4.82E+04	-5.62E-06	4.80E+04	-8.51E-06	4.77E+04	-1.26E-05	4.74E+04
9.2	-1.86E-06	4.84E+04	-2.95E-06	4.81E+04	-4.68E-06	4.78E+04	-7.08E-06	4.74E+04	-1.07E-05	4.71E+04	-1.58E-05	4.68E+04
9.3	-2.34E-06	4.79E+04	-3.71E-06	4.76E+04	-5.89E-06	4.72E+04	-8.91E-06	4.68E+04	-1.35E-05	4.65E+04	-2.00E-05	4.61E+04
9.4	-2.95E-06	4.74E+04	-4.68E-06	4.70E+04	-7.41E-06	4.66E+04	-1.12E-05	4.61E+04	-1.70E-05	4.57E+04	-2.51E-05	4.53E+04
9.5	-3.72E-06	4.68E+04	-5.89E-06	4.63E+04	-9.33E-06	4.58E+04	-1.41E-05	4.53E+04	-2.14E-05	4.48E+04	-3.16E-05	4.43E+04
9.6	-4.68E-06	4.61E+04	-7.41E-06	4.55E+04	-1.17E-05	4.49E+04	-1.78E-05	4.43E+04	-2.69E-05	4.38E+04	-3.98E-05	4.32E+04
9.7	-5.89E-06	4.52E+04	-9.33E-06	4.46E+04	-1.48E-05	4.39E+04	-2.24E-05	4.32E+04	-3.39E-05	4.26E+04	-5.01E-05	4.20E+04
9.8	-7.41E-06	4.43E+04	-1.17E-05	4.35E+04	-1.86E-05	4.28E+04	-2.82E-05	4.20E+04	-4.27E-05	4.14E+04	-6.31E-05	4.07E+04
9.9	-9.33E-06	4.32E+04	-1.48E-05	4.24E+04	-2.34E-05	4.15E+04	-3.55E-05	4.07E+04	-5.37E-05	4.00E+04	-7.94E-05	3.93E+04
10.0	-1.17E-05	4.20E+04	-1.86E-05	4.11E+04	-2.95E-05	4.02E+04	-4.47E-05	3.94E+04	-6.76E-05	3.86E+04	-1.00E-04	3.79E+04
10.1	-1.48E-05	4.07E+04	-2.34E-05	3.97E+04	-3.72E-05	3.88E+04	-5.62E-05	3.79E+04	-8.51E-05	3.72E+04	-1.26E-04	3.65E+04
10.2	-1.86E-05	3.93E+04	-2.95E-05	3.83E+04	-4.68E-05	3.73E+04	-7.08E-05	3.65E+04	-1.07E-04	3.57E+04	-1.58E-04	3.51E+04
10.3	-2.34E-05	3.78E+04	-3.72E-05	3.69E+04	-5.89E-05	3.59E+04	-8.91E-05	3.51E+04	-1.35E-04	3.43E+04	-2.00E-04	3.37E+04
10.4	-2.95E-05	3.64E+04	-4.68E-05	3.54E+04	-7.41E-05	3.45E+04	-1.12E-04	3.37E+04	-1.70E-04	3.30E+04	-2.51E-04	3.25E+04
10.5	-3.72E-05	3.50E+04	-5.89E-05	3.41E+04	-9.33E-05	3.32E+04	-1.41E-04	3.25E+04	-2.14E-04	3.18E+04	-3.16E-04	3.13E+04
10.6	-4.68E-05	3.37E+04	-7.41E-05	3.28E+04	-1.17E-04	3.20E+04	-1.78E-04	3.13E+04	-2.69E-04	3.08E+04	-3.98E-04	3.03E+04
10.7	-5.89E-05	3.24E+04	-9.33E-05	3.16E+04	-1.48E-04	3.09E+04	-2.24E-04	3.03E+04	-3.39E-04	2.98E+04	-5.01E-04	2.94E+04
10.8	-7.41E-05	3.13E+04	-1.17E-04	3.06E+04	-1.86E-04	2.99E+04	-2.82E-04	2.94E+04	-4.27E-04	2.90E+04	-6.31E-04	2.86E+04
10.9	-9.33E-05	3.02E+04	-1.48E-04	2.96E+04	-2.34E-04	2.91E+04	-3.55E-04	2.86E+04	-5.37E-04	2.83E+04	-7.94E-04	2.80E+04
11.0	-1.17E-04	2.94E+04	-1.86E-04	2.88E+04	-2.95E-04	2.83E+04	-4.47E-04	2.80E+04	-6.76E-04	2.77E+04	-1.00E-03	2.74E+04
11.1	-1.48E-04	2.86E+04	-2.34E-04	2.81E+04	-3.72E-04	2.77E+04	-5.62E-04	2.74E+04	-8.51E-04	2.72E+04	-1.26E-03	2.70E+04
11.2	-1.86E-04	2.79E+04	-2.95E-04	2.76E+04	-4.68E-04	2.72E+04	-7.08E-04	2.70E+04	-1.07E-03	2.67E+04	-1.58E-03	2.66E+04
11.3	-2.34E-04	2.74E+04	-3.72E-04	2.71E+04	-5.89E-04	2.68E+04	-8.91E-04	2.66E+04	-1.35E-03	2.64E+04	-2.00E-03	2.63E+04
11.4	-2.95E-04	2.69E+04	-4.68E-04	2.67E+04	-7.41E-04	2.64E+04	-1.12E-03	2.63E+04	-1.70E-03	2.61E+04	-2.51E-03	2.60E+04
11.5	-3.72E-04	2.66E+04	-5.89E-04	2.63E+04	-9.33E-04	2.62E+04	-1.41E-03	2.60E+04	-2.14E-03	2.59E+04	-3.16E-03	2.58E+04
11.6	-4.68E-04	2.63E+04	-7.41E-04	2.61E+04	-1.17E-03	2.59E+04	-1.78E-03	2.58E+04	-2.69E-03	2.57E+04	-3.98E-03	2.57E+04
11.7	-5.89E-04	2.60E+04	-9.33E-04	2.59E+04	-1.48E-03	2.57E+04	-2.24E-03	2.57E+04	-3.39E-03	2.56E+04	-5.01E-03	2.55E+04
11.8	-7.41E-04	2.58E+04	-1.17E-03	2.57E+04	-1.86E-03	2.56E+04	-2.82E-03	2.55E+04	-4.27E-03	2.55E+04	-6.31E-03	2.54E+04
11.9	-9.33E-04	2.56E+04	-1.48E-03	2.56E+04	-2.34E-03	2.55E+04	-3.55E-03	2.54E+04	-5.37E-03	2.54E+04	-7.94E-03	2.53E+04
12.0	-1.17E-03	2.55E+04	-1.86E-03	2.54E+04	-2.95E-03	2.54E+04	-4.47E-03	2.53E+04	-6.76E-03	2.53E+04	-1.00E-02	2.52E+04

## **Appendix B**

**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: Bennington, Vermont**

Item		Description
I	Case Study Number	1
II	PWS Description	
	a. Raw Water Supply	Surface water
	b. Water Quality	
	1. Raw	Low pH, alkalinity and calcium content.
	2. Treated	Coagulated water pH 4.5 - 5.0, alkalinity < 5 mg CaCO <sub>3</sub> /L.
	c. Treatment	Filtration, chlorination.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	<ul style="list-style-type: none"> <li>Community blood lead monitoring program revealed elevated levels in 1977.</li> <li>Material survey of the distribution system found that one-third of the system was served by lead service lines.</li> <li>Tap samples were collected, finding lead levels as high as 0.86 mg/L.</li> <li>Theoretical performance of carbonate passivation.</li> </ul>
	b. Demonstration Testing	
	1. Flow-Through	NA
	2. Static	NA
	3. Full-Scale	Implemented pH and alkalinity adjustment treatment.
	c. Full-Scale Confirmation	
	1. Tap sampling	Monthly first-draw and running tap samples from 10 targeted sites.
	2. WQP-DIS	pH, alkalinity, and scale analysis using X-ray diffraction.
	3. WQP-POE	pH and alkalinity
IV	Testing Program Description	
	a. Constraints	Due to the elevated blood lead levels in the population, treatment installation had to be easily and quickly installed and operable.
	b. Priorities	
	1. Primary	Reduce lead levels in consumers' tap water.
	2. Secondary	
	c. Treatment Alternatives	pH and alkalinity adjustment: Increase pH to 8.0-8.5 and increase alkalinity to above 25 mg CaCO <sub>3</sub> /L.
	d. Monitoring programs	<ul style="list-style-type: none"> <li>Tap monitoring for lead in first-draw and running samples: 1977-1991.</li> <li>pH and alkalinity monitoring in distribution system and at the POEs: 1977-1991.</li> <li>Evaluate scale on lead service line pipes using X-ray diffraction: 1977.</li> </ul>
	e. QA/QC Elements	See Reference

**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: Bennington, Vermont**

Item		Description
V	<b>Testing Results</b>	
	a. Corrosion Control Performance	<ul style="list-style-type: none"> <li>Average monthly lead levels in first-draw tap samples were reduced from a high of 250 ug/L to approximately 20 ug/L lead within six-months of operations.</li> <li>Ongoing monitoring has showed a continual decline in lead levels in first-draw tap samples with early 1991 data indicating lead levels less than 10 ug/L.</li> <li>X-ray diffraction analysis confirmed scale formation consisting of cerrusite (<math>PbCO_3</math>) and hydrocerrusite (<math>Pb_3(CO_3)_2(OH)_2</math>).</li> </ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	Initial operation of the sodium bicarbonate and sodium hydroxide feed systems was manual, and targeted values for pH and alkalinity were not always achieved. To improve treatment consistency, automated operational controls were installed in 1990.
VI	<b>Notes/Qualifications</b>	NA
VII	<b>Reference(s)</b>	Vinci, A. 1992. Bennington, Vermont Corrosion Control Studies with the Bicarbonate/pH System. Technical comments submitted to USEPA in response to the proposed Lead and Copper Rule from Church & Dwight, Company, 469 N. Harrison St., Princeton, NJ, 08543-5297.

**PWS Characterization:** *Low pH, Alkalinity, & Calcium*  
**PWS Name & Location:** *MWRA, Boston, Massachusetts*

Item		Description
I	Case Study Number	2
II	PWS Description	
	a. Raw Water Supply	Unfiltered surface water.
	b. Water Quality	
	1. Raw	Low turbidity, low pH-Alkalinity-Calcium.
	2. Treated	Finished water quality: pH 6.5-6.7; Total hardness 12 mg CaCO <sub>3</sub> /L; Alkalinity 12 mg CaCO <sub>3</sub> /L; Total dissolved solids 37 mg/L.
	c. Treatment	Chlorination, ammoniation, fluoridation.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	NA
	b. Demonstration Testing	
	1. Flow-Through	NA
	2. Static	NA
	3. Full-Scale	Alternative treatments were implemented system-wide.
	c. Full-Scale Confirmation	
	1. Tap sampling	Diagnostic and verification tap sampling was performed.
	2. WQP-DIS	pH, alkalinity, and inhibitor residual
	3. WQP-POE	pH, alkalinity, and inhibitor residual
IV	Testing Program Description	
	a. Constraints	Treatment alternative had to be compatible with the facilities of an unfiltered supply.
	b. Priorities	
	1. Primary	Reduce lead levels at consumers' taps.
	2. Secondary	Reduce copper levels at consumers' taps.
	c. Treatment Alternatives	Orthophosphate inhibitor and pH adjustment.
	d. Monitoring programs	First-draw tap sampling for lead and copper; WQP-POE; and WQP-DIS.
	e. QA/QC Elements	NA

**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: MWRA, Boston, Massachusetts**

Item		Description
V	<b>Testing Results</b>	
	a. Corrosion Control Performance	<ul style="list-style-type: none"> <li>Six-month trial full-scale treatment using zinc orthophosphate:               <ol style="list-style-type: none"> <li>Initial passivation dose of 13 mg/L used for several weeks, then reduced the dosage to between 3.2 and 4.5 mg/L.</li> <li>Initial increase in tap lead levels observed, then slow decline in lead noted toward the end of the six month period.</li> <li>Algal growth appeared to be stimulated in the open, finished water storage reservoirs due to the additional phosphate content.</li> </ol> </li> <li>pH Adjustment using sodium hydroxide was subsequently installed.               <ol style="list-style-type: none"> <li>Lead and copper levels in first-draw samples were reduced by increased pH.</li> <li>Researchers noted that when the pH dropped from pH 9 to below pH 8, the lead levels increased.</li> </ol> </li> </ul>
	b. Secondary Impacts	<ul style="list-style-type: none"> <li>Algal growth was stimulated in the open, treated water reservoirs when zinc orthophosphate was used.</li> <li>Dirty water complaints arose with the introduction of the phosphate inhibitor.</li> </ul>
	c. Treatment Issues	<ul style="list-style-type: none"> <li>A high pH at the POE was necessary to maintain targeted pH values throughout the distribution system.</li> </ul>
VI	<b>Notes/Qualifications</b>	The poor performance of the zinc orthophosphate inhibitor is most likely the result of an excessively low pH for its effectiveness. Had the treated water pH been increased to above 7, it is likely that the performance results would have been improved.
VII	<b>Reference(s)</b>	Karalekas, P.C. et al. 1983. Control of Lead, Copper, and Iron Pipe Corrosion in Boston. <i>Journal AWWA</i> . 75(2):92-95.

**PWS Characterization:** *Low pH, Alkalinity, & Calcium*  
**PWS Name & Location:** *FCWD, Fort Collins, Colorado*

Item		Description
I	Case Study Number	3
II	PWS Description	
	a. Raw Water Supply	Poudre River & Horsetooth Reservoir
	b. Water Quality	
	1. Raw	Cold, low turbidity, moderate pH, low alkalinity and low calcium
	2. Treated	Coagulated Water: pH = 5.8 - 7.2, Alkalinity = 5-25 mg CaCO <sub>3</sub> /L, and Calcium = 20-30 mg CaCO <sub>3</sub> /L
	c. Treatment	Alum coagulation, fluoridation, and chlorination
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	Analogous Systems: Seattle, WA and Bennington, VA Theoretical: Evaluation of carbonate passivation Process Testing: Marble Chip Testing
	b. Demonstration Testing	
	1. Flow-Through	NA
	2. Static	NA
	3. Full-Scale	Implemented pH/alkalinity adjustment full-scale in two stages to optimize treatment.
	c. Full-Scale Confirmation	
	1. Tap sampling	First-draw samples from public taps: 1981 - 1992.
	2. WQP-DIS	WQP-DIS for pH, alkalinity and calcium: 1981 - 1992.
	3. WQP-POE	WQP-POE for pH, alkalinity and calcium: 1981 - 1992.
IV	Testing Program Description	
	a. Constraints	<ul style="list-style-type: none"> <li>Brewery which required consistent, moderate pH.</li> <li>Land application of sewage sludge limited by copper.</li> <li>Use of phosphate inhibitor questionable due to wastewater treatment requirements and public acceptance.</li> </ul>
	b. Priorities	
	1. Primary	Reduce copper levels in tap water and sewage sludge.
	2. Secondary	No adverse effects on other water treatment goals or aesthetic quality of the treated water.
	c. Treatment Alternatives	<p>pH and alkalinity adjustment using lime and sodium bicarbonate.</p> <p>Stage 1: pH Goal = 7.6-7.8 &amp; Alk Goal &gt; 30 mg CaCO<sub>3</sub>/L.</p> <p>Stage 2: pH Goal = 7.8-8.0 &amp; Alk Goal = 35-45 mg CaCO<sub>3</sub>/L</p>
	d. Monitoring programs	<ul style="list-style-type: none"> <li>In-line pH monitors located after stabilization chemical feed points.</li> <li>Alkalinity measured at POE every 4-hours.</li> <li>8-10 sampling stations monitoring monthly for first-draw copper and WQP-DIS.</li> </ul>
	e. QA/QC Elements	Process controls.



**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: FCWD, Fort Collins, Colorado**

Item		Description
V	<b>Testing Results</b>	
	a. Corrosion Control Performance	<ul style="list-style-type: none"> <li>• Tap copper levels were reduced from high levels ranging between 0.8-1.0 mg/L to maximum values between 0.2-0.4 mg/L.</li> <li>• Sludge metal content reduced: Copper 20%; Lead 30-50%.</li> </ul>
	b. Secondary Impacts	<ul style="list-style-type: none"> <li>• Post-filtration turbidity spikes with lime addition</li> <li>• Elevating pH caused post-precipitation of manganese during period of reservoir stratification. This caused brown water complaints. FCWD installed potassium permanganate pretreatment to control soluble manganese present after filtration.</li> </ul>
	c. Treatment Issues	<ul style="list-style-type: none"> <li>• Process control for stable and consistent final pH took between one and two years to debug.</li> <li>• FCWD has been able to achieve the pH and alkalinity goals over 90 percent of the time.</li> <li>• For more cost-effective treatment, FCWD is installing carbon dioxide in lieu of sodium bicarbonate.</li> <li>• Redundant feed systems are being installed for lime and carbon dioxide to ensure continuous operation.</li> </ul>
VI	<b>Notes/Qualifications</b>	<p>During the first incident of manganese post-precipitation, FCWD stopped the pH adjustment portion of their corrosion control program. Within days of this, copper levels began to increase in first-draw tap samples, and the copper and lead content of the sewage sludge increased during the period when pH adjustment was not being practiced. This indicated to FCWD that (1) effective corrosion control could only be assured if continuously practiced; and (2) while the loss of corrosion protection became apparent in a matter of days, it took several weeks to months to regain the control conditions experienced prior to the treatment interruption.</p>
VII	<b>Reference(s)</b>	<p>Smith, M. et al. 1992. <i>Corrosion Control Studies and Strategies - Fort Collins, Colorado</i>. AWWA Corrosion Control Seminar (Denver, CO).</p> <p>Kuchenrither, R.D. et al. 1988. <i>Sludge Quality Benefits Realized from Drinking Water Stabilization</i>. Proc. Annual WPCF Conference.</p> <p>Elmund, G.K. et al. 1986. <i>Stabilization of a Finished Water: Fort Collins, Colorado</i>. Proc Joint Regional AWWA-WPCA Conference.</p>

**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: Bureau of Water, Portland, Oregon**

Item		Description
I	Case Study Number	4
II	PWS Description	
	a. Raw Water Supply	Unfiltered surface water supply
	b. Water Quality	
	1. Raw	Low pH, alkalinity, and calcium
	2. Treated	Finished water quality: pH 6.9; Total hardness 14 mg CaCO <sub>3</sub> /L; Alkalinity 10 mg CaCO <sub>3</sub> /L; Total dissolved solids 24 mg/L.
	c. Treatment	Chlorination/chloramination.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	Theoretical: Carbonate passivation Analogous Systems: Seattle, Washington
	b. Demonstration Testing	
	1. Flow-Through	Coupons and copper tubing
	2. Static	NA
	3. Full-Scale	NA
	c. Full-Scale Confirmation	
	1. Tap sampling	NA
	2. WQP-DIS	NA
	3. WQP-POE	NA
IV	Testing Program Description	
	a. Constraints	Compatibility with unfiltered surface water treatment facilities.
	b. Priorities	
	1. Primary	Assess the corrosion rates of domestic plumbing materials.
	2. Secondary	Determine the most cost effective approach to treatment.
	c. Treatment Alternatives	Existing treatment at two locations in the distribution system: 1. Pipe rig consisted of coupon (6) flow-through units with black iron, galvanized steel, copper, lead, lead:tin solder-coated copper, and asbestos-cement. 2. A single loop (220 feet) of lead:tin soldered copper tubing was also included in the pipe rig. Soldered joints were placed every 20-feet. 3. Pipe rig 1 was located at the source of supply with a free chlorine residual of 1 mg/L. 4. Pipe rig 2 was located several miles from the source and chloramines were added.
	d. Monitoring programs	Metal leaching and water quality parameters entering the pipe loops systems.
	e. QA/QC Elements	NA

**PWS Characterization: Low pH, Alkalinity, & Calcium**  
**PWS Name & Location: Bureau of Water, Portland, Oregon**

Item		Description
V	Testing Results	
	a. Corrosion Control Performance	<ul style="list-style-type: none"><li>• Equilibrium corrosion rates appeared to result after six months of operation for all of the materials.</li><li>• Based on the test coupons, lead corrosion rates increased with free chlorine as compared to chloramines.</li><li>• All other materials experienced comparable corrosion rates (on the basis of coupons) regardless of the disinfectant present.</li><li>• The copper tubing with lead:tin solder showed increased corrosion activity with chloramines as compared to the free chlorine loop.</li></ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	The source of lead in first-draw tap samples appeared to be the lead-based solder as confirmed by the pipe loop testing program. No treatment was recommended since the City of Portland had instituted a lead ban on plumbing materials for domestic supply systems.
VI	Notes/Qualifications	Portland has participated in the AWWARF Pipe Loop Study, and more information on the corrosion behavior of it system, especially as it relates to first-draw tap samples will be available in the final report.
VII	Reference(s)	Treweek, G.P. et al. 1985. Pilot-plant Simulation of Corrosion in Domestic Pipe Materials. <i>Journal AWWA</i> . 77(10):74-82.

**PWS Characterization:** Low pH, Alkalinity, & Calcium  
**PWS Name & Location:** SWD, Seattle, Washington

Item		Description
I	Case Study Number	5
II	PWS Description	
	a. Raw Water Supply	Two unfiltered surface water supplies - Tolt & Cedar Rivers
	b. Water Quality	
	1. Raw	Low pH, alkalinity, calcium and mineral content.
	2. Treated	Finished water quality: pH 5.7-6.2; Alkalinity 3-5 mg CaCO <sub>3</sub> /L; Chlorine residual 0.2-0.4 mg/L.
	c. Treatment	Chlorination and fluoridation.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	Theoretical: Carbonate passivation
	b. Demonstration Testing	
	1. Flow-Through	Series of pilot loop tests conducted prior to full-scale treatment installation.
	2. Static	NA
	3. Full-Scale	Corrosion rate and metal leaching studies conducted after installing treatment.
	c. Full-Scale Confirmation	
	1. Tap sampling	First-draw tap samples collected from 300 homes in service area.
	2. WQP-DIS	pH, alkalinity, chlorine residual, dissolved oxygen, conductivity
	3. WQP-POE	pH, alkalinity, chlorine residual
IV	Testing Program Description	
	a. Constraints	Compatibility with unfiltered, surface water facilities.
	b. Priorities	
	1. Primary	Reducing the corrosion activity in the distribution system toward lead, copper, zinc (galvanized piping) and iron.
	2. Secondary	Reliability and operational feasibility of the selected treatment process.
	c. Treatment Alternatives	<ul style="list-style-type: none"> <li>Pipe loop testing evaluated pH/alkalinity alternatives and orthophosphate corrosion inhibitors:               <ol style="list-style-type: none"> <li>Recirculating pipe loops were constructed using 1/2-inch copper tubing in which a bead of 50:50 lead:tin solder was attached longitudinally in the piping.</li> <li>Copper tubing lengths were 6-8 inches individually; then several were connected using plastic tubing.</li> <li>Treated water was circulated through a test loop using a peristaltic pump cyclically.</li> </ol> </li> <li>Corrosion rate testing was performed using linear polarization techniques once full-scale treatment was installed.</li> </ul>
	d. Monitoring programs	Metal leaching, corrosion rates, and water quality parameters were monitored in the flow-through testing apparatus and in the full-scale systems once the recommended treatment was installed.
	e. QA/QC Elements	See Reference Materials.

**PWS Characterization:** Low pH, Alkalinity, & Calicum  
**PWS Name & Location:** SWD, Seattle, Washington

Item		Description
V	Testing Results	
	a. Corrosion Control Performance	<ul style="list-style-type: none"><li>pH and alkalinity adjustment was the recommended treatment on the basis of the flow-through testing program.</li><li>After installation, reductions in tap lead and copper levels (as first-draw samples) of 12 and 60 percent were found within the first year of operation.</li><li>Electrochemical testing results showed a 50% decrease in corrosion rates on new copper plumbing with greater decreases in aged materials.</li><li>Short-term variations in copper corrosion rates were found to be strongly correlated to free chlorine (direct relationship), and to a lesser degree with pH (inverse relationship).</li></ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	pH and alkalinity adjustment took place gradually over the first year of operations, increasing the average pH to 7.8-8.3 and the average alkalinity to 15-17 mg CaCO3/L.
VI	Notes/Qualifications	
VII	Reference(s)	<p>Reiber, S.H. et al. 1987. Corrosion Monitoring and Control in the Pacific Northwest. <i>Journal AWWA</i>. 79(2):71-74.</p> <p>Stone, A. et al. 1987. The Effects of Short-term Changes in Water Quality on Copper and Zinc Corrosion Rates. <i>Journal AWWA</i>. 79(2):75-82.</p> <p>Reiber, S.H. et al. 1987. <i>Corrosion in Water Distribution Systems of the Pacific Northwest</i>. EPA 600/S2-87-042.</p> <p>Herrara, C.E. et al. 1984. <i>Seattle Distribution System Corrosion Control Study - Volume 2: Tolt River Water Pilot Plant Study</i>. EPA 600/2-84-065.</p> <p>Hoyt, B.P. et al. 1982. <i>Seattle Distribution System Corrosion Control Study - Volume 1: Cedar River Water Pilot Plant Study</i>. EPA 600/2-82-026.</p>

**PWS Characterization:** *Low pH, High Alkalinity & Calcium*  
**PWS Name & Location:** *Oakwood, Ohio*

Item		Description
I	Case Study Number	6
II	PWS Description	
	a. Raw Water Supply	Two well-fields
	b. Water Quality	
	1. Raw	Lower pH, High alkalinity and calcium, elevated iron.
	2. Treated	Finished water quality: pH 7.1; Total hardness 200 mg CaCO <sub>3</sub> /L; Alkalinity 370 mg CaCO <sub>3</sub> /L.
	c. Treatment	Water from one well-field removes iron through green-sand filtration and is then softened using zeolite softening. The treated water is then blended with water from the other well-field and chlorinated prior to distribution.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	NA
	b. Demonstration Testing	
	1. Flow-Through	Pipe loop study to evaluate corrosion rates before and after softening.
	2. Static	NA
	3. Full-Scale	Tap sampling before and after softening to determine difference in corrosion activity.
	c. Full-Scale Confirmation	
	1. Tap sampling	First-draw tap samples at sites receiving water only from Well-field 1 prior to being blended with water from the second well-field.
	2. WQP-DIS	pH, alkalinity, hardness
	3. WQP-POE	pH, alkalinity, hardness

**PWS Characterization:** Low pH, High Alkalinity & Calcium  
**PWS Name & Location:** Oakwood, Ohio

Item		Description
IV	Testing Program Description	
	a. Constraints	NA
	b. Priorities	
	1. Primary	Determine if softening would impact corrosion rates.
	2. Secondary	
	c. Treatment Alternatives	<ul style="list-style-type: none"> <li>Flow-through testing program:               <ol style="list-style-type: none"> <li>Two pipe rigs were constructed with one receiving unsoftened water and the other receiving softened water.</li> <li>Each rig had three test loops: black iron, lead, and pipe sleeves consisting of black iron, copper, lead:tin solder-coated copper, and galvanically coupled (copper and lead solder) coupons (4 coupons of each).</li> <li>Each pipe loop (black iron and lead) was pre-conditioned by receiving only hard water for 7-months.</li> <li>The pipe sleeves received hard and soft water throughout the entire testing period.</li> <li>Flowrate conditions for the pipe sleeves were: 0.5 gpm at 5 psi for six days, with one day of standing time.</li> <li>Flowrate conditions for the pipe loops were: Iron pipe, recirculating rate of 1 gpm with an effluent rate of 0.0172 gpm; Lead pipe flow-through rate of 0.5 gpm for 16 hours with an 8-hour standing time cyclically operated.</li> <li>Each pipe rig operated two lead loops: one was of new material and the second was excavated (old material) from the distribution system.</li> </ol> </li> <li>Full-scale evaluation testing program consistent of sampling consumers' homes for metals and water quality parameters while receiving hard and softened water.</li> </ul>
	d. Monitoring programs	<ul style="list-style-type: none"> <li>Flow-through testing program: In addition to the WQP monitoring performed were the following:               <ul style="list-style-type: none"> <li>Pipe loops: Metal leaching</li> <li>Pipe Sleeves: Metal leaching and coupon weight-loss</li> </ul>               Dissolved oxygen depletion was used to calculate the corrosion rates in the iron pipe loops.             </li> <li>Full-scale evaluation: First-draw samples for lead, copper, pH, alkalinity, and hardness.</li> </ul>
	e. QA/QC Elements	See Reference

**PWS Characterization:** Low pH, High Alkalinity & Calcium  
**PWS Name & Location:** Oakwood, Ohio

Item	Description	
V	Testing Results	
	a. Corrosion Control Performance	<ul style="list-style-type: none"><li>Flow-through testing program:<ol style="list-style-type: none"><li><i>Coupon results</i>: no difference was observed on the basis of weight-loss between hard and softened water, except in the case with galvanically-coupled coupons where a modest increase in corrosion rate was noted for the softened condition. Generally, corrosion rates did decrease over time.</li><li><i>Iron pipe loop results</i>: At the end of the 7-month pre-conditioning period, the iron loops produced similar corrosion rate results.</li><li><i>Lead pipe loop results</i>: At the end of the 7-month pre-conditioning period, significant variability in the performance of loops were observed as follows:<ul style="list-style-type: none"><li>New &amp; Old did not perform alike;</li><li>Old &amp; Old did not perform alike;</li></ul>While the two new loops behaved statistically comparable, the variability was high with 90% confidence intervals ranging between 32 and 72 percent of the mean values of lead.</li></ol></li><li>Full-scale evaluation - No significant difference in metal concentrations were found before and after the installation of softening treatment.</li></ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	NA
VI	Notes/Qualifications	<ul style="list-style-type: none"><li>Flow-through testing program:<ol style="list-style-type: none"><li>Replicate performance of pipe loops showed a large variability in metal leaching.</li><li>Results from the evaluation of hard and softened water conditions have yet to be published.</li></ol></li><li>Full-scale evaluation - 23 homes were included in the tap monitoring program. Of these, 12 had point of entry softeners which were to be bypassed during the sampling day. However, this means that about 50 percent of the sites had already been exposed to softened water prior to the utility installing its ion exchange treatment unit.</li></ul>
VII	Reference(s)	Wysock, B.M. et al. 1991. A Study of the Effect of Municipal Ion Exchange Softening on the Corrosion of Lead, Copper, and Iron in Water Systems. Proc. Annual AWWA Conference (Philadelphia, PA).



**PWS Characterization: Moderate pH, High Alkalinity & Calcium**  
**PWS Name & Location: Fort Shawnee, Ohio**

Item		Description
I	Case Study Number	7
II	PWS Description	
	a. Raw Water Supply	Groundwater
	b. Water Quality	
	1. Raw	Moderate pH, high alkalinity and hardness, and elevated iron and hydrogen sulfide levels.
	2. Treated	Final water quality: pH 7.3-8.0; Total hardness 250-300 mg CaCO <sub>3</sub> /L; Alkalinity 290-350 mg CaCO <sub>3</sub> /L; sulfate 206-330 mg SO <sub>4</sub> /L; chloride 16-45 mg Cl/L; and carbon dioxide 18-28 CO <sub>2</sub> mg/L.
	c. Treatment	Well water is aerated and filtered for iron and hydrogen sulfide removal; split treatment for zeolite softening.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	<ul style="list-style-type: none"> <li>Copper pitting failures occurring in domestic cold water piping in relatively new condominiums.</li> <li>Investigators determined that excessive carbon dioxide and oxygen primarily responsible for corrosive behavior of the treated water. This was thought to be exacerbated by the higher sulfate and chloride content of the water supply.</li> <li>Raising the pH to approximately 8.3 would reduce the carbon dioxide content of the finished water.</li> </ul>
	b. Demonstration Testing	
	1. Flow-Through	Pipe loop testing was performed.
	2. Static	NA
	3. Full-Scale	NA
	c. Full-Scale Confirmation	
	1. Tap sampling	NA
	2. WQP-DIS	NA
	3. WQP-POE	NA

**PWS Characterization: Moderate pH, High Alkalinity & Calcium**  
**PWS Name & Location: Fort Shawnee, Ohio**

Item	Description														
<b>IV</b>	<p><b>Testing Program Description</b></p> <table> <tr> <td>a. Constraints</td><td> <ul style="list-style-type: none"> <li>Treatment facility was not continuously staffed.</li> <li>Chemical storage was located in an unheated building, so that freezing was a concern for the winter months.</li> </ul> </td></tr> <tr> <td>b. Priorities</td><td></td></tr> <tr> <td>1. Primary</td><td>Reduce the copper pitting failures in home-owners' plumbing systems.</td></tr> <tr> <td>2. Secondary</td><td>Operational feasibility.</td></tr> <tr> <td>c. Treatment Alternatives</td><td> <ul style="list-style-type: none"> <li>Two pipe loops constructed of 50-by-1 meter lengths of type L copper tubing - 3/4 inch diameter, soldered with 50:50 lead:tin solder.</li> <li>Pipe loop 1 received existing finished water; Pipe loop 2 received finished water treated with soda ash to raise the pH to approximately 8.3.</li> <li>Loops were operated cyclically: running for 10-minutes; standing for 110-minutes for sixteen hours; then standing for 8-hours.</li> </ul> </td></tr> <tr> <td>d. Monitoring programs</td><td> <ul style="list-style-type: none"> <li>Water quality parameters were measured entering the pipe loops, but no metal leaching data was collected.</li> <li>After one-years's operation, the tubes were removed and physically inspected for corrosion activity.</li> <li>Energy dispersive spectroscopy (EDS) and microchemical analysis were used to confirm the corrosion byproducts present on the interior walls of the copper piping.</li> </ul> </td></tr> <tr> <td>e. QA/QC Elements</td><td>NA</td></tr> </table>	a. Constraints	<ul style="list-style-type: none"> <li>Treatment facility was not continuously staffed.</li> <li>Chemical storage was located in an unheated building, so that freezing was a concern for the winter months.</li> </ul>	b. Priorities		1. Primary	Reduce the copper pitting failures in home-owners' plumbing systems.	2. Secondary	Operational feasibility.	c. Treatment Alternatives	<ul style="list-style-type: none"> <li>Two pipe loops constructed of 50-by-1 meter lengths of type L copper tubing - 3/4 inch diameter, soldered with 50:50 lead:tin solder.</li> <li>Pipe loop 1 received existing finished water; Pipe loop 2 received finished water treated with soda ash to raise the pH to approximately 8.3.</li> <li>Loops were operated cyclically: running for 10-minutes; standing for 110-minutes for sixteen hours; then standing for 8-hours.</li> </ul>	d. Monitoring programs	<ul style="list-style-type: none"> <li>Water quality parameters were measured entering the pipe loops, but no metal leaching data was collected.</li> <li>After one-years's operation, the tubes were removed and physically inspected for corrosion activity.</li> <li>Energy dispersive spectroscopy (EDS) and microchemical analysis were used to confirm the corrosion byproducts present on the interior walls of the copper piping.</li> </ul>	e. QA/QC Elements	NA
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<b>V</b>	<p><b>Testing Results</b></p> <table> <tr> <td>a. Corrosion Control Performance</td><td> <ul style="list-style-type: none"> <li>EDS and microchemical analyses confirmed that pipe loops treated with soda ash showed cuprous oxide and calcium carbonate coatings on the surface of the pipe walls. No pitting corrosion was evident in any of the pipes extracted from the soda ash-treated loop.</li> <li>Pitting corrosion was evident in pipes exposed to water not treated with soda ash based on visual inspection. EDS and microchemical analysis confirmed the following:               <ol style="list-style-type: none"> <li>Green tubercles overlaying pits consisted principally of copper carbonate (malachite) mixed with copper sulfate;</li> <li>Pits examined by scanning electron microscopy were found to contain cubic crystalline byproducts. EDS findings indicated that these byproducts contained major quantities of copper with semiminor quantities of sulfate, and trace amounts of chloride.</li> </ol> </li> <li>Tap sampling was not performed, but following installation of soda ash treatment, the pitting failures of copper, domestic piping ceased within 6-months.</li> </ul> </td></tr> <tr> <td>b. Secondary Impacts</td><td>NA</td></tr> <tr> <td>c. Treatment Issues</td><td>Average dosage of soda ash was 35 mg/L for a pH goal of 8.1-8.3.</td></tr> </table>	a. Corrosion Control Performance	<ul style="list-style-type: none"> <li>EDS and microchemical analyses confirmed that pipe loops treated with soda ash showed cuprous oxide and calcium carbonate coatings on the surface of the pipe walls. No pitting corrosion was evident in any of the pipes extracted from the soda ash-treated loop.</li> <li>Pitting corrosion was evident in pipes exposed to water not treated with soda ash based on visual inspection. EDS and microchemical analysis confirmed the following:               <ol style="list-style-type: none"> <li>Green tubercles overlaying pits consisted principally of copper carbonate (malachite) mixed with copper sulfate;</li> <li>Pits examined by scanning electron microscopy were found to contain cubic crystalline byproducts. EDS findings indicated that these byproducts contained major quantities of copper with semiminor quantities of sulfate, and trace amounts of chloride.</li> </ol> </li> <li>Tap sampling was not performed, but following installation of soda ash treatment, the pitting failures of copper, domestic piping ceased within 6-months.</li> </ul>	b. Secondary Impacts	NA	c. Treatment Issues	Average dosage of soda ash was 35 mg/L for a pH goal of 8.1-8.3.								
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<b>VI</b>	<b>Notes/Qualifications</b>														
<b>VII</b>	<b>Reference(s)</b> Cohen, A. and J.R. Meyers. 1987. Mitigating Copper Pitting through Water Treatment. <i>Journal AWWA</i> . 79(2):58-61.														

**PWS Characterization: Moderate pH, High Alkalinity & Calcium**  
**PWS Name & Location: Pinellas County, Florida**

Item		Description
I	Case Study Number	8
II	PWS Description	
	a. Raw Water Supply	Deep well water
	b. Water Quality	
	1. Raw	High hardness and alkalinity with elevated hydrogen sulfide
	2. Treated	Finished water quality: pH 7.6-7.85; Total hardness 200-214 mg CaCO <sub>3</sub> /L; Alkalinity 200-211 mg CaCO <sub>3</sub> /L; chlorine residual 2.5 mg/L.
	c. Treatment	Reduced draft aeration of well water for hydrogen sulfide removal; pH adjustment using caustic soda, and chlorination.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	NA
	b. Demonstration Testing	
	1. Flow-Through	Screening of options for full-scale evaluation and pipe rig operation using various water quality conditions to determine the cause and effect of corrosion problems as a function of dissolved oxygen, pH, and corrosion inhibitor.
	2. Static	NA
	3. Full-Scale	In-situ testing using pipe rig systems after full-scale treatment installation.
	c. Full-Scale Confirmation	
	1. Tap sampling	First-draw tap samples for copper.
	2. WQP-DIS	pH, dissolved oxygen, carbon dioxide, inhibitor residual
	3. WQP-POE	pH, dissolved oxygen, inhibitor dose
IV	Testing Program Description	
	a. Constraints	NA
	b. Priorities	
	1. Primary	Minimize copper corrosion.
	2. Secondary	Not adversely affect lead corrosion.
	c. Treatment Alternatives	<ul style="list-style-type: none"> <li>• Screening testing evaluated four corrosion inhibitors, combinations of ortho- and polyphosphates for four months.</li> <li>• Full-scale evaluation:               <ol style="list-style-type: none"> <li>1. Coupons and flow-through test racks were installed at 11 locations in the distribution system.</li> <li>2. The test racks were operated at a flow of 2 gpm for a month at a time.</li> <li>3. The recommended orthophosphate inhibitor treatment was installed full-scale.</li> <li>4. Corrosion rates were evaluated for 6-months prior to installing phosphate treatment and 6-months after treatment was in-place.</li> </ol> </li> <li>• Demonstration flow-through testing:               <ol style="list-style-type: none"> <li>1. Four pipe rigs were constructed with lead, copper, and mild steel flat coupons (4 each), and galvanized steel and copper pipe inserts (2 each).</li> <li>2. Flow-through testing was conducted for 6-months under varying combinations of dissolved oxygen, pH, and inhibitor dosages.</li> </ol> </li> </ul>

**PWS Characterization:** *Moderate pH, High Alkalinity & Calcium*  
**PWS Name & Location:** *Pinellas County, Florida*

Item		Description
	d. Monitoring programs	<ul style="list-style-type: none"> <li>Screening tests utilized Virchem 2902 corrosion test units which measure corrosion rates through electrochemical measurements.</li> <li>Full-scale evaluation: corrosion rates were measured via weight loss measurements for the coupons and pipe inserts. First-draw tap samples were also collected from 25 sites in the affected area of the distribution system.</li> <li>Demonstration flow-through testing: corrosion rates were measured using weight loss.</li> </ul> <p>Water quality parameters were measured throughout all phases of the testing program.</p>
	e. QA/QC Elements	NA
<b>V</b>	<b>Testing Results</b>	
	a. Corrosion Control Performance	<p>Screening tests indicated that orthophosphate was most effective in controlling copper and lead corrosion.</p> <ul style="list-style-type: none"> <li>Full-scale evaluation: <ol style="list-style-type: none"> <li>Reductions in copper corrosion rate of 30% after adding 1 mg/L orthophosphate.</li> <li>Lead corrosion reduction was nominal, approximately 10%.</li> <li>Tap sampling results showed copper and lead reductions in first-draw samples of 47% and 40%, respectively.</li> <li>Wastewater influent copper levels were noted to be reduced by 57%.</li> </ol> </li> <li>Demonstration flow-through testing <ol style="list-style-type: none"> <li>Optimum orthophosphate dose was 1.0 mg/L as PO<sub>4</sub>.</li> <li>Lead corrosion rates increased slightly when the pH was increased from 7.5 to 8.1.</li> <li>A pH value of 7.7 was found to be optimum with dissolved oxygen concentrations of 0.4-6.0 mg/L.</li> <li>Dissolved oxygen concentrations between 0.4 and 6 mg/L has little effect on corrosion rates in the presence of 1 mg/L orthophosphate.</li> </ol> </li> </ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	NA
<b>VI</b>	<b>Notes/Qualifications</b>	
<b>VII</b>	<b>Reference(s)</b>	Powell, R.M. et al. 1991. Corrosion in Water Distribution Systems. AWWA/EPA Corrosion Control Seminar (Chicago, IL).

**PWS Characterization:** *High pH, Alkalinity & Calcium*  
**PWS Name & Location:** *Water District No. 1, Johnson County, Kansas*

Item		Description
I	Case Study Number	9
II	PWS Description	
	a. Raw Water Supply	Kansas River and Missouri River
	b. Water Quality	
	1. Raw	High turbidity, hardness and alkalinity; Moderate pH.
	2. Treated	Finished water quality: pH 9.1, Total hardness 122 - 130 mg CaCO <sub>3</sub> /L, Alkalinity 53 mg CaCO <sub>3</sub> /L, TDS 300 mg/L, chloride 35-70 mg/L, sulfate 135-200 mg/L.
	c. Treatment	Lime softening, chloramination, and polyphosphate addition.
III	Corrosion Control Study Elements	
	a. Desk-top Evaluation	<ul style="list-style-type: none"> <li>Reviewed historical water quality data: raw, treated, and within the distribution system.</li> <li>Removed several unlined fittings from the distribution system for visual inspection.</li> <li>Reviewed technical literature about corrosion behavior for high pH waters.</li> <li>Surveyed other lime softening utilities about corrosion problems encountered in their distribution systems.</li> <li>Recommendation was to try to achieve calcium carbonate deposits for corrosion protection.</li> </ul>
	b. Demonstration Testing	
	1. Flow-Through	NA
	2. Static	NA
	3. Full-Scale	Coupon inserts in distribution system during three phases of treatment modification.
	c. Full-Scale Confirmation	
	1. Tap sampling	NA
	2. WQP-DIS	NA
	3. WQP-POE	pH, alkalinity, calcium, temperature

**PWS Characterization:** *High pH, Alkalinity & Calcium*  
**PWS Name & Location:** *Water District No. 1, Johnson County, Kansas*

Item		Description
<b>IV</b>	<b>Testing Program Description</b>	
	a. Constraints	Compatibility of treatment approach for lime softening facility. Polyphosphate addition was practiced for calcium sequestering prior to filtration to prevent excessive deposition on filter media.
	b. Priorities	
	1. Primary	Based on customer complaints, reduce iron corrosion.
	2. Secondary	Determine if optimal corrosion for iron control would also benefit the District for lead and copper corrosion control.
	c. Treatment Alternatives	Three phases of softening modification: 1. Phase 1 - Increase pH to 9.3; 2. Phase 2 - Increase pH to 9.5 and increase final alkalinity and calcium content to 140-160 mg CaCO <sub>3</sub> /L and 90-110 mg CaCO <sub>3</sub> /L, respectively. 3. Phase 3 - Increase pH to 9.8-10.0
	d. Monitoring programs	Removal and replacement of mild steel coupons placed in-situ in the distribution system every 3-months. Finished water quality monitored to achieve goals of each treatment phase.
	e. QA/QC Elements	NA
<b>V</b>	<b>Testing Results</b>	
	a. Corrosion Control Performance	<ul style="list-style-type: none"> <li>Phase 2 treatment corrosion rates were 35% lower than Phase 1 corrosion rates based on the mild steel coupon results.</li> <li>A 40% decrease in customer complaints was observed overall (across Phases 1 and 2); however, complaints in areas of the service area composed of older, unlined cast iron mains showed little improvement.</li> </ul>
	b. Secondary Impacts	NA
	c. Treatment Issues	NA
<b>VI</b>	<b>Notes/Qualifications</b>	<ul style="list-style-type: none"> <li>The corrosion behavior of the distribution system is still be evaluated through the Phase 3 treatment modifications.</li> <li>Elimination of the polyphosphate feed is being considered in order to improve the deposition of calcium carbonate.</li> </ul>
<b>VII</b>	<b>Reference(s)</b>	Goold, R.R. et al. 1991. Enhancing Distribution System Water Quality at Water District No. 1. Proc. Annual AWWA Conference (Philadelphia, PA).

## Appendix C

### ***Statistical Evaluation of Corrosion Control Performance Data***

#### ***Non-parametric Statistics***

The use of non-parametric statistical measures may assist PWSs in interpreting the findings of demonstration tests. These methods of data analysis are independent of the normality of data distributions, and provide measures of the relationship between distinct data populations. In applying the non-parametric methods to lead and copper testing results, the type of question which they may answer is: Is the population of lead levels from experimental condition 'A' higher, lower, or the same as those from experimental conditions 'B'?

The Wilcoxon Test (also known as the Mann-Whitney Test, the U-Test, or the Rank Sums Test) is a non-parametric alternative to the two sample Student's t-Test. Using the lead concentration data presented in the flow-through example in Section 4.9.1 (Table 4-8), the Wilcoxon Test may be used to select the treatment method which minimized lead levels in simulated first-flush samples. The problem may be stated as follows:

- Are the lead levels from Pipe Loop 1 larger than those from Pipe Loop 2?
- Are the lead levels from Pipe Loop 1 larger than those from Pipe Loop 3?
- Are the lead levels from Pipe Loop 2 larger than those from Pipe Loop 3?

By applying the Wilcoxon Test to answer the three questions above we

will be able to determine whether lime addition (Loop 2) or phosphate inhibitors (Loop 3) provide improvements in lead corrosion control, and whether either method is superior to the other.

The first step is to rank the two populations of data under evaluation as one set of data, from the smallest to the largest value. Table C-1 presents the results of ranking the lead concentration data for our three comparison conditions. Note that when a value occurs multiple times in the data base, the mean rank is assigned to each occurrence.

The next step is to sum the ranking for the data each of the populations. For example, Loop 1 and Loop 2 rankings were summed under the first comparison condition as shown in Table C-1, resulting in 1,504 and 979, respectively. The U-value may be calculated based on the sum of the ranks,  $W_i$ , and the number of observations,  $n_i$ , as follows:

$$U_i = W_i - n_i(n_i + 1)/2$$

with the statistic U being the smaller of  $U_1$  and  $U_2$  for any comparison condition. The mean and variance for any population of U values may be calculated as:

$$\text{Mean } U = n_1 * n_2 / 2$$

$$\text{Var } U = n_1 * n_2 * (n_1 + n_2 + 1) / 12$$

The U statistic approximates a normal distribution when both  $n_1$  and  $n_2$  are greater than 8.

To test the null hypothesis that the two data groups come from the same population, the z-statistic is calculated as a function of U, Mean U, and

**Table C-1. Wilcoxon Test for Comparing Flow-Through Testing Results**

Comparison 1 — Loop 1:2			Comparison 2 — Loop 1:3			Comparison 3 — Loop 2:3		
Pb,ppb	Rank	Loop	Pb,ppb	Rank	Loop	Pb,ppb	Rank	Loop
45	1	2	30	1	3	30	1	3
48	2	2	38	2	3	38	2	3
48	3	2	42	3	3	42	3	3
52	4	2	45	4	3	45	4.5	2
52	5	2	50	5	3	45	4.5	3
52	6	2	51	6	3	48	6.5	2
53	7	2	52	7	3	48	6.5	2
55	8	2	54	8	3	50	8	3
57	9	2	55	9	3	51	9	3
58	10	2	58	10	3	52	11.5	2
60	11.5	1	60	11	1	52	11.5	2
60	11.5	2	62	13	1	52	11.5	2
62	13	1	62	13	3	52	11.5	3
63	14	1	62	13	3	53	14	2
68	16	1	63	15	1	54	15	3
68	16	1	65	16.5	3	55	16.5	2
68	16	2	65	16.5	3	55	16.5	3
72	19.5	1	68	20.5	1	57	18	2
72	19.5	2	68	20.5	1	58	19	3
72	19.5	2	68	20.5	3	58	20.5	2
72	19.5	2	68	20.5	3	60	20.5	2
75	22.5	1	68	20.5	3	62	22.5	3
75	22.5	2	68	20.5	3	62	22.5	3
76	24	2	70	24	3	65	24.5	3
78	26	1	72	26	1	65	24.5	3
78	26	1	72	26	3	68	28	2
78	26	1	72	26	3	68	28	3
79	27.5	2	73	28	3	68	28	3
79	27.5	2	75	30	3	68	28	3
80	31	1	75	31	1	68	28	3
80	31	2	75	31	3	70	31	3
80	31	2	76	32	3	72	34	2
82	33	1	78	34.5	1	72	34	2
85	34.5	1	78	34.5	1	72	34	2
85	34.5	2	78	34.5	1	72	34	3
87	36.5	1	78	34.5	3	72	34	3
87	36.5	2	80	37.5	1	73	37	3
90	38	2	80	37.5	3	75	39	2
91	39	1	81	39	3	75	39	3
92	41	1	82	40.5	1	75	39	3
92	41	1	82	40.5	3	76	41.5	2
92	41	2	85	42	1	76	41.5	3



**Table C-1. Wilcoxon Test for Comparing Flow-Through  
Testing Results (continued)**

Comparison 1 — Loop 1:2			Comparison 2 — Loop 1:3			Comparison 3 — Loop 2:3		
Pb,ppb	Rank	Loop	Pb,ppb	Rank	Loop	Pb,ppb	Rank	Loop
95	43.5	1	87	43	1	78	43	3
95	43.5	2	91	44	1	79	44.5	2
96	45	2	92	45.5	1	79	44.5	2
97	46.5	1	92	45.5	1	80	47	2
97	46.5	2	95	47	1	80	47	2
100	48.5	1	97	48	1	80	47	3
100	48.5	2	98	49	3	81	49	3
103	50.5	1	100	50	1	82	50	3
103	50.5	2	102	51.5	3	85	51	2
107	52	1	102	51.5	3	87	52	2
108	53.5	2	103	53	1	90	53	2
108	53.5	2	107	54	1	92	54	2
110	55.5	1	109	55	3	95	55	2
110	55.5	2	110	56	1	96	56	2
112	57.5	1	112	57.5	1	97	57	2
112	57.5	1	112	57.5	1	98	58	3
115	59	1	115	59.5	1	100	59	2
118	60	1	115	59.5	3	102	60.5	3
125	61	1	118	61	1	102	60.5	3
126	62	1	125	62	1	103	62	2
130	63	2	126	63.5	1	108	63.5	2
132	64	1	126	63.5	3	108	63.5	2
135	65	2	132	65	1	109	65	3
138	66	1	138	66	1	110	66	2
162	67	1	162	67	1	115	67	3
175	68	1	175	68	1	126	68	3
190	69	1	190	69	1	130	69	2
205	70	1	205	70	1	135	70	2

StdDev U (STDDEV U = square root of Var U) as follows:

$$z = (U - \text{Mean } \bar{U}) / \text{StdDev } U$$

Table C-2 presents sum of ranks, U values, and z values for the three comparison conditions for the lead concentration data from the flow through testing results using the above calculations.

To test the comparison conditions, the z values are evaluated with respect to  $z_\alpha$  values for the alpha (i.e.,  $\alpha$ ) level of significance desired. In the lead testing example,  $Z_{0.01} = 2.575$  was used to evaluate the three comparisons. When  $z < -z_\alpha$ , then the distribution of the data with the larger U value is said to be *stochastically* higher than the other population's distribution. For the first comparison condition, for example, the larger U value corresponded to Loop 1 data and the z value was less than  $-z_\alpha$ , then the lead levels found in the control loop (Loop 1) are higher than those found from the lime addition loop (Loop 2). Conversely, when  $z > z_\alpha$ , then the distribution of the data with the larger U value is said to be stochastically lower than the other population's distribution.

The results shown in Table C-2 indicate that Loop 2 and Loop 3 lead levels were significantly different from Loop 1 lead levels, but not significantly different from each other. Additionally, the z values show that Loop 1 (control) lead levels were higher than both Loop 2 and Loop 3 lead concentrations.

### ***Parametric Statistics***

Water quality measurements obtained during corrosion control studies will seldom represent the one true value

present at the time of sampling. Errors will be associated with both sampling techniques and analytical measurements. It is generally assumed that the errors indigenous to these measured values are random errors. Therefore, the mean of several values should be a better indicator of the true value than a single measurement.

The configuration in which the data are arranged is called its distribution, and many statistical procedures utilize a normal distribution in which the data are symmetrical and form a bell shaped curve. Parametric statistics make use of these procedures.

Most sample sets of water quality data do not exactly form a bell shaped curve, and they are sometimes "transformed" by the application of some mathematical function into another form which more closely follows a normal distribution. As an example of this procedure, the lead data used for the example of Section 4.9.1 (See Table 4-8) will be transformed into the log normal mode by using the log of the individual determinations.

Parametric statistics were used to compare the two treatments with the control. The data were investigated for skewness recognizing that as the moment coefficient of skewness approaches zero that the data approach a more normal distribution. If the distribution is normal, or can be made more normal by a transformation, the statistical techniques based on a normal distribution are appropriate; otherwise they are only approximations and the use of non-parametric statistics as presented previously in Appendix C may be more appropriate.

**Table C-2. Summary of Wilcoxon Test Measures for Comparing the Performance of Lead Corrosion Control Alternatives**

Condition	Measurements			
<b>Sum of Ranks, W</b>	<b>Loop 1</b>	<b>Loop 2</b>	<b>Loop 3</b>	
Comparison 1	1,504.0	979.0	-----	
Comparison 2	1,612.5	-----	874.5	
Comparison 3	-----	1,366.0	1,199.0	
<b>U — Values</b>	<b>Loop 1</b>	<b>Loop 2</b>	<b>Loop 3</b>	<b>Resultant</b>
Comparison 1	874.0	349.0	-----	349.0
Comparison 2	982.5	-----	244.5	244.5
Comparison 3	-----	736.0	569.0	569.0
<b>Key Statistical Measures</b>	<b>Mean_U</b>	<b>Var_U</b>	<b>z</b>	<b>Finding</b>
Comparison 1	612.5	7,248.0	-3.1	Loop 1 > Loop 2
Comparison 2	612.5	7,248.0	-4.3	Loop 1 > Loop 3
Comparison 3	612.5	7,248.0	-0.5	No Difference

The skewness coefficient,  $\gamma$ , is defined as:

$$\gamma = \frac{m_3}{m_2^{1.5}}$$

where:

$$m_2 = \frac{1}{n} \sum x_i^2 - \bar{x}^2$$

$$m_3 = \frac{1}{n} \sum x_i^3 - \frac{3}{n} \bar{x} \sum x_i^2 + 2\bar{x}^3$$

$x_i$  = individual samples,  $i = 1$  to  $n$

$\bar{x}$  = mean

Table C-3 gives the calculated means, moments, and skewness coefficients for the lead data of Table 4-8 for both normal and log normal distributions. The smaller coefficients for the log normal distribution were used as indicators that the data would more appropriately adapt to parametric statistics using a logarithmic transformation.

**Table C-3. Skewness Coefficients**

<b>Normal:</b>	<b>Loop 1</b>	<b>Loop 2</b>	<b>Loop 3</b>
mean	0.1038	0.0791	0.0711
m <sub>2</sub>	0.0012	0.0005	0.0005
m <sub>3</sub>	0.0001	5.83 x 10 <sup>-6</sup>	5.76 x 10 <sup>-6</sup>
γ	1.21	0.47	0.60
<b>Log Normal:</b>			
mean	-1.0058	-1.1204	-1.1683
m <sub>2</sub>	0.0182	0.0163	0.0178
m <sub>3</sub>	0.0013	-0.0001	-0.0007
γ	0.53	-0.04	-0.32

The student's t statistic was used to compare paired data among the three loops. These results are shown in both Table C-4 and Table 4-9. Student's t can be defined as:

$$t = \frac{\bar{d}}{s_{\bar{d}}}$$

where the numerator represents the mean difference between paired sample data and the denominator represents the standard deviation appropriate to the difference between the sample means. These values are then compared to standard statistical tables to determine if there is a statistical difference in treatments.

**Table C-4. Student's t Values**

<b>Comparison</b>	<b>t</b>
Loop 1 and Loop 2	5.46***
Loop 1 and Loop 3	6.98***
Loop 2 and Loop 3	2.87**
<b>Notes:</b> All test data transformed to logarithmic values ** Highly significant difference at the 0.01 level *** Extremely significant difference at the 0.001 level	

As indicated in the text of Section 4.9.1, the last 10 weeks of data were independently examined. These data are shown in Table C-5. Again, prior to conducting an examination of the data using the Student's t statistic, a log transformation was made, i.e.:

0.078 was used as  $\log 0.078 = -1.1079$   
 0.060 was used as  $\log 0.060 = -1.2218$ ;  
 etc.

Using Student's t and examining the paired data between loops for week 26 through week 35 gave the results

shown in Table C-6. Standard statistical tables were used to compare the t value against with the sign ignored, i.e., either a positive or negative value was acceptable. For 9 degrees of freedom (10 sets of data minus 1), the t statistics are:

t @ 0.05 level = 2.262

Significant difference

t @ 0.01 level = 3.250

Highly significant difference

t @ 0.001 level = 4.781

Extremely significant difference

**Table C-5. Lead Data from Final 10 Weeks of Testing**

Week No.	Loop 1	Loop 2	Loop 3
26	0.078	0.080	0.080
27	0.060	0.052	0.062
28	0.092	0.058	0.054
29	0.075	0.045	0.058
30	0.087	0.053	0.045
31	0.063	0.060	0.052
32	0.072	0.055	0.068
33	0.068	0.052	0.030
34	0.080	0.048	0.051
35	0.091	0.057	0.042

**Table C-6. Calculate Student's t Values for Final 10 Weeks**

Comparison	t
Loop 1 and Loop 2	4.88**
Loop 1 and Loop 3	3.60**
Loop 2 and Loop 3	0.67, not significant
Notes: All test data transformed to logarithmic values ** t value > 3.25, highly significant difference	

Thus the analysis shows that each treatment is significantly different from the control, but there is no apparent statistical difference between treatments.